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RESEARCH ARTICLE

Lighting design affects the uniformity and growth of plants in a vertical farming system

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Abstract

Light is essential for plant production and has various effects on plant quality. Vertical farms typically use light-emitting diodes (LEDs) as light sources. However, the cost of LEDs varies with wattage and the initial installation costs are generally high. Therefore, to explore more cost-effective LED designs, we aimed to investigate the impact of red LED chips density on light distribution and plant growth under the same total electricity consumption. To this end, we exposed baby leaf soybean [*Glycine max* (L.) Merr.].; 5 days) and kale (*Brassica oleracea* var. *acephala*; 18 days) to LEDs light with different arrangements of red and white chips. Plants were exposed to either 2 W chips with a red:white ratio of 4:64 (2W4R treatment) or 1 W chips with a red:white ratio of 8:64 (1W8R treatment) across the entire LED bar. We observed that the distribution of red light in the cultivation room differed depending on the density of the red LED chips. We found that arranging low-power red LED chips at narrow intervals resulted in uniform light distribution across the entire cultivation bed, positively affecting crop growth. Baby leaf soybean and kale exhibited uniform growth under 1W8R and growth was particularly enhanced in kale. This may be because of the dense leaf structure of kale, which promotes photosynthesis under a uniform light environment. The results of this study demonstrate that a favorable light environment can be created by altering the position and distribution of red LED chips, thereby inducing uniform growth in plants.

Keywords

baby leaf soybean; kale; lighting; light distribution; red LED; vertical farming

Introduction

A vertical farm is a plant production system that may be considered a plant factory (1). Vertical farms can efficiently produce plants by increasing space utilization on multiple floors in limited indoor spaces (2). Furthermore, vertical farming environments typically have fewer pests and diseases; therefore, plants can be grown using fewer pesticides. Additionally, climatic factors that contribute to plant growth, such as temperature, light, humidity and nutrient solution composition, can be easily controlled within a vertical farming system. Environmental control in vertical farms also shows the potential to regulate plant nutrient and functional material content (3). Consequently, plants can be produced without time and space restrictions and crop production efficiency can be improved by artificially adjusting the light environment, leading to higher production efficiency compared to greenhouses (4). Environmental control systems in vertical farms can be optimized to address the problem of reduced production due to changing climatic conditions (5). Vertical farming has grown rapidly in the United States (6) and the United Kingdom (7) over the past decade and has gained increasing attention as a research topic.

In recent years, the mass production of sprouts and microgreens has increased worldwide. Researchers reported that plants can be categorized as sprouts, microgreens and baby leaf depending on the cultivation period, edible parts and harvest stage (8). The baby leaf stage refers to the period where true leaves are consumed, typically harvested between 20-40 days after sowing. Sprouts and young leafy vegetables (i.e., baby leaf vegetables) are highly nutritious because they contain higher amounts of phytonutrients and minerals, such as ascorbic acid and beta carotene, than mature leaves (9, 10). In the early stages of seed germination, biochemical changes inside seeds induce the accumulation of metabolites such as free amino acids and fatty acids (11), which increases the total nutrient content of sprouts (12). Soybeans [*Glycine max* (L.) Merr.] are suitable for sprout production and consumption owing to their short production cycles (13). Soybean sprouts contain various nutrients, including isoflavones (14) and ascorbic acid (15). Meanwhile, Chinese kale (*Brassica oleracea* var. *alboglabra* Bailey), a crop belonging to the *Brassicaceae* family, which includes broccoli and cabbage, has a relatively short growth period compared to other crops. This has led to various research projects being conducted on vertical farms using kale. Kale is commonly used in salads because of its high nutritional value, making it a commercially valuable vegetable (16). Furthermore, kale is rich in health-promoting phytochemicals, such as ascorbic acid, carotenoids, flavonoids and other phenols and it has higher antioxidant activity than many other vegetables, including other cruciferous vegetables (17). Additionally, kale consumption has been shown to reduce the risk of degenerative and chronic diseases such as cancer and diabetes (18). Therefore, producing baby leaf soybeans and kale in vertical farming can meet the growing demand for these nutritious vegetables.

Light is essential for inducing photosynthetic biosynthesis and photomorphogenesis (19) and is a critical factor that positively affects the concentration of phytochemicals in plants (20). Light-emitting diodes (LEDs) are the most commonly used light sources in vertical farms and have several advantages over other light sources (21). The advantages of LEDs arise from their small size, durability, long lifetime, low emission temperature, relatively low cost compared with other light sources and the ability to easily tune specific wavelengths to elicit different responses in the target plant (22). Although leafy vegetables are highly productive crops in vertical farms, high-quality commercialization of plants is required, along with measures to increase production. Previous studies have reported the effects of adjusting the optical environment, such as LED light intensity and light quality, to increase plant growth and phytochemical accumulation. The light quality composition is a characteristic of LEDs and a variable that has various effects on phytochemical accumulation. For example, red light induces photosynthesis (23), promotes growth and increases stem length, leaf number and hypocotyl length (24) in plants.

Red LEDs play an important role in promoting plant growth and uniform illumination is effective for producing stable, high-quality plants with maximum commercial value (25). The light distribution varies depending on the spacing of the LED chips; the more uniform the light distribution, the less impact there is from differences in light intensity (26). High-wattage LED chips can focus light on a specific area, which can degrade plant quality and productivity, leading to uneven plant growth. One solution is to maintain the number of white chips in the lighting module and increase the number of red chips. However, this approach underutilizes the capacity of high-wattage red chips, resulting in high costs. Therefore, it is necessary to design light modules for vertical farming that use red chips with adequate wattage and high efficacy to address both non uniform light distribution and high-cost problems.

Compared to other cultivation facilities such as greenhouses and open fields, vertical farms achieve more efficient space utilization on the same area of land, resulting in higher plant production (27). However, due to the high electricity consumption of artificial lighting, which is essential for vertical farms, the operating costs are higher than those of other cultivation facilities. Therefore, it is necessary to develop methods to reduce the operating costs of vertical farms. The most effective way to reduce these costs is to use the light emitted from artificial light sources for plant cultivation as efficiently as possible (28). Increasing the uniformity of light distribution on the plant cultivation beds can improve efficiency. Uniform light from artificial sources is essential for the economic feasibility of vertical farms; therefore, lamp efficiency (photons emitted per J of electricity) should be considered.

While several studies have reported the effects of light intensity and quality on the growth and phytochemical accumulation of baby leaf soybean (29) and kale (30) in vertical farms, there is insufficient research on the effects of light distribution (31). Uniform light distribution is associated with stable photosynthetic photon flux density (PPFD), which represents the number of photosynthetically active photons per second that fall onto a given surface and is one of the major factors influencing plant growth (32). The radiative nature of the light source causes a PPFD deviation between the overlapping and non-overlapping areas of each LED chip (33). Therefore, the spacing of LED chips is expected to result in variations in PPFD within the space influenced by LEDs, leading to uneven plant growth. The distribution of light can be controlled through the design of LED chips and as the uniformity of light distribution increases, the deviation in light received by plants decreases, leading to consistent and uniform plant production. In this study, we aimed to investigate the effect of red LED chip spacing on the uniformity of baby leaf soybean and kale growth under 2 different lighting configurations with the same total power consumption.

Materials and Methods

Plant materials and growth conditions for baby leaf soybean

Soybean seeds [*Glycine max* (L.) Merr.] were germinated on an Oasis medium (Rootcubes®; Smithers-Oasis Company, Kent, OH, USA) with 96 cavities per tray and cultivated using a hydroponic method involving a deep-flow technique system. Six trays were arranged per treatment. The cultivation experiment was conducted at the Smart Farm Cube (35°09'27.3"N 128°04'56.5"E) located at the Naedong Campus of Gyeongsang National University, where the internal environment was maintained at a temperature of 23 °C (Supplementary Fig. S1), relative humidity of 60 %, light intensity of 180 μ mol m^{-2} s^{-1} of PPFD and photoperiod of 16:8 (light : dark) hours. The experimental site comprised 2 areas and the cultivation area (120 × 90 × 41.5 cm) was divided for each treatment (Supplementary Fig. S2). Soybean seedlings were irradiated with white LED light for 6 days. Light was applied with variously designed LEDs for 5 days starting on the 7th day after sowing (DAS). Soybeans were irrigated with 50 mL of distilled water once a day until 6 DAS and Hoagland nutrient solution (Supplementary Table S1, pH 6.0, electrical conductivity 1260 µs cm^{-1}) was used for irrigation from 6 DAS until the harvest.

Experimental design and light conditions for baby leaf soybean

Red (LH321H 1 W 660 nm Deep Red and LH351H 2 W 660 nm Deep Red; Samsung Electronics, Suwon, Korea) and white (LM301H EVO; Samsung Electronics, Suwon, Korea) LEDs were used as light sources for plant growth. We utilized 2 LED bars with different arrangements of white and red chips (Supplementary Fig. S3). The 2W4R treatment group was exposed to 2 W LEDs with a red: white chip ratio of 4:64, while the 1W8R treatment group was exposed to 1 W LEDs with a red: white chip ratio of 8:64. The length of the LED bar used in the experiment was 120 cm and the intervals between the red chips of the 2W4R and 1W8R LED bars were 30 and 15 cm respectively. Additionally, the 2W4R and 1W8R LEDs, which had red chip configurations with different power consumptions, were designed to have no effect due to differences in light quality (Supplementary Table S2). Two LED bars were installed at 40 cm intervals, and LEDs were installed 20 cm above the plant canopy. A portable spectro radiometer (LI-180; Li-Cor, Lincoln, NE, USA) was used to measure the intensity of each light source. The light intensity was measured at 12 points in each cultivation area, 20 cm away from the light source (Supplementary Fig. S2). The light intensity of both treatment groups was regulated to an average of 180 μmol m^{-2} s^{-1}. The light treatment of the soybean plants lasted for 5 days, with a photoperiod set at 16:8 (light : dark) hours. Additionally, the light intensity from LEDs close to the outside of the cultivation bed was measured at 15 points to evaluate the effect of the position of the red chips on light parameters and plant growth (Supplementary Fig. S3). Light treatment was performed when 2–3 leaves appeared on each plant.

Growth characteristics of baby leaf soybean

The fresh weight (FW) was measured 6 times per treatment, setting 96 individuals harvested from one tray as one replicate. Plant height was measured by randomly selecting 6 plants from one tray and setting them as one replicate, thus conducting the measurement 6 times per treatment. The dry weight (DW) was estimated by dividing the value measured after oven-drying (WOF-155; Daihan, Wonju, Republic of Korea) the individuals that had their FW measured at 70 °C for 3 days by the number of individuals harvested from one tray. The aerial parts of the samples were dried and stored at 4 °C for material analysis. The stem thickness index (STI) was calculated based on the DW of the aerial parts per unit plant height, using the previously described method (34) as shown below:

$$\mathrm{STI} = \frac{plant\ height\ (cm)}{DW\ (mg)} \qquad \text{............(Eqn. 1)}$$

Plant materials and growth conditions for Kale

Kale seeds (*Brassica oleracea* var. *acephala*) used in the experiment were of the ‘Matjjang’ variety, a part of the Green Kale species. The seeds were germinated on a sponge with 90 cavities per tray and from 6 DAS, they were cultivated using a hydroponic method involving a deep-flow technique system. The environmental conditions of the vertical farming system were maintained at a temperature of approximately 23 °C. The kale plants were grown under white LEDs until 19 DAS and from 19 DAS, they were grown for 18 days under LEDs designed with different densities of red chips and then harvested. Until 5 DAS, the kale was irrigated with distilled water and starting from 6 DAS, Hoagland nutrient solution (pH 6.0, electrical conductivity 1260 µs cm^{-1}) was used for irrigation.

Experimental design and light conditions for Kale

The light sources used in the experiment were the same as those used for the soybeans. The light treatment lasted for 18 days, with a photoperiod set at 16:8 (light : dark) hours.

Growth characteristics of Kale

The FW was measured in 8 uniform plants randomly selected from each treatment. Leaf area was measured using an area meter (LI-3100; Li-Cor, Lincoln, NE, USA). The DW was measured after oven-drying for 3 days at 70 °C. The aerial parts of the samples were dried and stored at 4 °C for material analysis. Specific leaf weight (SLW) was calculated based on the DW of the aerial parts per unit leaf area, using the previously described method (35) as shown below:

$$\mathrm{SLW} = \frac{DW\ (g)}{leaf\ area\ (cm^2)} \qquad \text{..........(Eqn. 2)}$$

Photosynthesis in Kale

A portable photosynthesis system (LI–6400; Li-Cor, USA) was used to measure the photosynthetic rate of the third and fourth leaves of 6 plants per treatment replicate.

The reference leaf temperature, relative humidity, CO$_2$ concentration, flow rate and light intensity inside the cuvette were maintained at 25 °C, 60 %, 500 ppm, 400 mol s^{-1} and 150 µ mol m^{-2} s^{-1} respectively.

Statistical analysis

Statistical analysis of all data from baby leaf soybean and kale was conducted using one-way analysis of variance with different light sources as variables. Duncan's multiple range test was used to separate the mean values ($p < 0.05$). Additionally, SAS software (version 9.4; SAS Institute Inc., Cary, NC, USA) was used to perform the statistical analysis. All figures and tables show the mean ± the standard error (SE).

Results

Baby leaf soybean

Light distribution under different light conditions

In the vertical farm, the distribution of red light in the cultivation bed clearly differed according to the density and location of the red chips (Fig. 1 and Supplementary Fig. S4). In the 2W4R treatment, red chips were located at positions 2, 6, 10 and 14. Both treatment groups were designed with an average PPFD of 100 at the red light wavelength. In a horizontal measurement across 15 points, the number of locations with values below 100 PPFD was 8 for 2W4R and 2 for 1W8R, indicating that the light distribution under 2W4R was less uniform than that under 1W8R (Fig. 1A). In contrast, the red chips in the 1W8R treatment were located at positions 1, 3, 5, 7, 9, 11, 13 and 15. The narrow spacing of the chips indicated a more uniform overall red PPFD distribution under the 1W8R treatment compared to that under the 2W4R treatment (Fig. 1B). The areas directly beneath the red chips exhibited higher PPFD values (Supplementary Fig. S3). The coefficient of variation (CV) was used as an index to quantify the light distribution of the LED bar, expressed as a % of the standard deviation divided by the average (36). The CV showed a lower value in the 1W8R treatment (11.14) compared to the 2W4R treatment (17.75), indicating a more uniform distribution of red light in the 1W8R. This uniform light distribution can promote uniform growth in plant height of baby leaf soybean.

Growth characteristics under different light distribution conditions

The dense arrangement of red LED chips did not affect soybean weight (FW and DW of shoots and roots) but induced significant differences in stem growth (Table 1). The average stem length of soybean plants in the 2W4R treatment group reached 13.01 cm, which was approximately 42 % greater than that in the 1W8R group. Furthermore, the STI was approximately 32 % higher in the 2W4R group than in the 1W8R group. This indicated that the 2W4R treatment led to thinner and more elongated soybean stems (Fig. 2 and 3). The heights of the soybean plants differed depending on the density of the red chips. The 2W4R treatment produced taller baby leaf soybean plants than the 1W8R treatment, especially at the red chip locations (Fig. 2A). However, the plant height in the 1W8R group was more uniform among individuals than in the 2W4R group (Fig. 2B). The stem thickness of baby leaf soybean plants was affected by the red light distribution (Fig. 3). There was a difference between the 2 treatments;

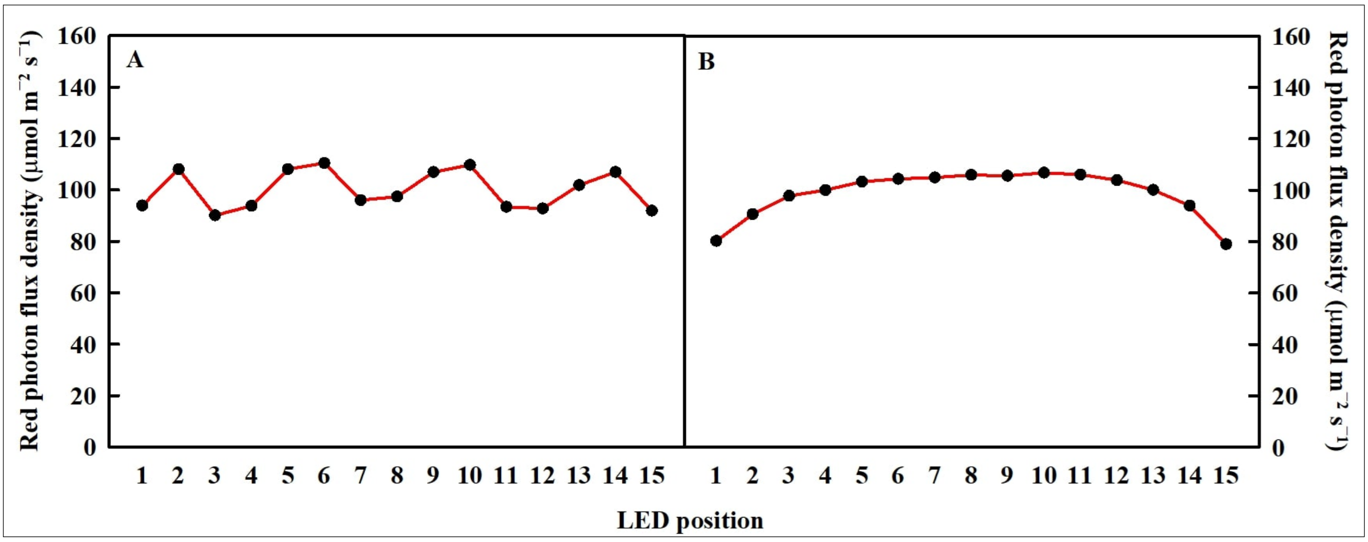

Fig. 1. The light distribution of the 2W4R (**A**) and 1W8R (**B**) treatments in a cultivation area for baby leaf soybean under the location of the red chips. The points from 1 to 15 indicate positions from left to right on the LED bar. Each point is located on a vertical line between the LED bar and the cultivation bed.

Table 1. The growth characteristics of baby leaf soybean exposed to different light sources (*n* = 6

Light source	Fresh weight (g)		Dry weight (g)		Stem height (cm)
	Shoot	Root	Shoot	Root	
2W4R	0.605 ± 0.006[z]	0.059 ± 0.008	0.061 ± 0.002	0.004 ± 0.001	13.01 ± 0.55^{a}
1W8R	0.586 ± 0.022	0.069 ± 0.016	0.059 ± 0.001	0.003 ± 0.001	9.10 ± 0.26^{b}
Significant	NS	NS	NS	NS	***

[z] Different letters within the same column indicate a statistically significant difference at $p< 0.05$ in Duncan's multiple range test. Values are means of at least three replicates ± S.E. [y] **NS** = non-significant; ***** is Significant at $P = 0.001$.

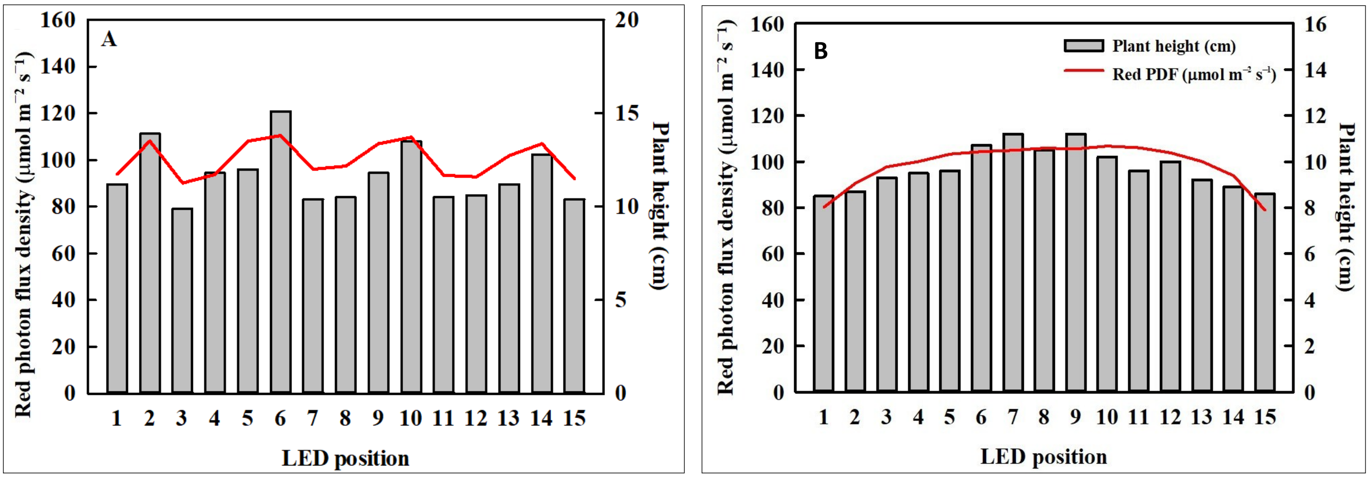

Fig. 2. Correlation between baby leaf soybean's heights and the red light distribution of LED bars treated with 2W4R (**A**) and 1W8R (**B**). The bars represent the plant height of the soybeans grown at each location and the red line represents the measured red photon flux density at each location.

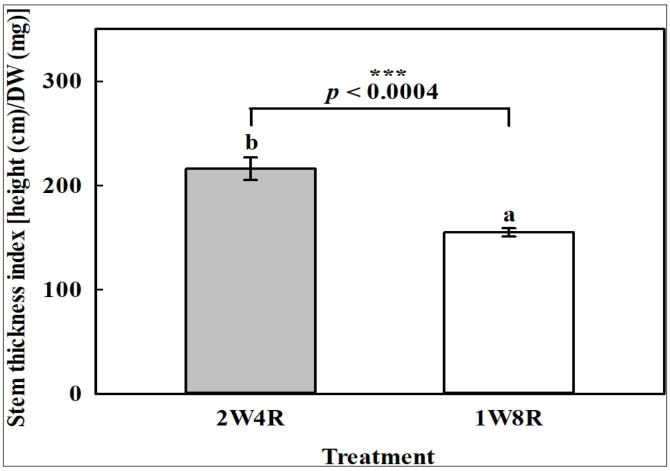

Fig. 3. The stem thickness index of baby leaf soybean exposed to different light sources (n = 6). Statistically significant differences are detected at $p < 0.05$ in Duncan's multiple-range test. ***** is $p < 0.001$. Different letters **a** and **b** indicate statistical differences between the treatments, **DW** is Dry weight.

the STI of baby leaf soybean plants was 17.9 % lower under the 1W8R treatment than under the 2W4R treatment.

Kale

Light distribution under different light conditions

The distribution of red light in the cultivation area of kale plants clearly differed according to the density of red chips, as was the case for baby leaf soybean (Fig. 4). The light intensity of the 2W4R treatment was high at positions 2, 6, 10 and 14 (where the red chips were present), resulting in an uneven light distribution. However, because the red chips in the 1W8R treatment were placed at narrower intervals, the overall red light distribution was more uniform than that of the 2W4R treatment. The CV was lower in the 1W8R treatment (9.22) than in the 2W4R treatment (12.94), indicating a more uniform light distribution in the 1W8R treatment.

Growth characteristics under different light distribution conditions

The FW of kale leaves was affected by differences in the uniformity of red light distribution caused by the variation in red chip density (Fig. 5). In the 2W4R group, the FW of kale leaves below the vertical line of the red chips increased, whereas in the 1W4R group, the FW of kale leaves appeared uniform within the growth section. Additionally, owing to the uniform distribution of red light, the 1W8R (9.22) treatment showed a lower CV than the 2W4R (12.94) treatment, resulting in even growth of kale. Uniform light distribution in the plant growth area, determined by the density of the red LED chips, caused positive changes in the thickness of kale leaves (Fig. 6), resulting in an approximately 13 % increase in the SLW in the 1W8R group compared with that in the 2W4R group.

Photosynthetic rate under different light distribution conditions

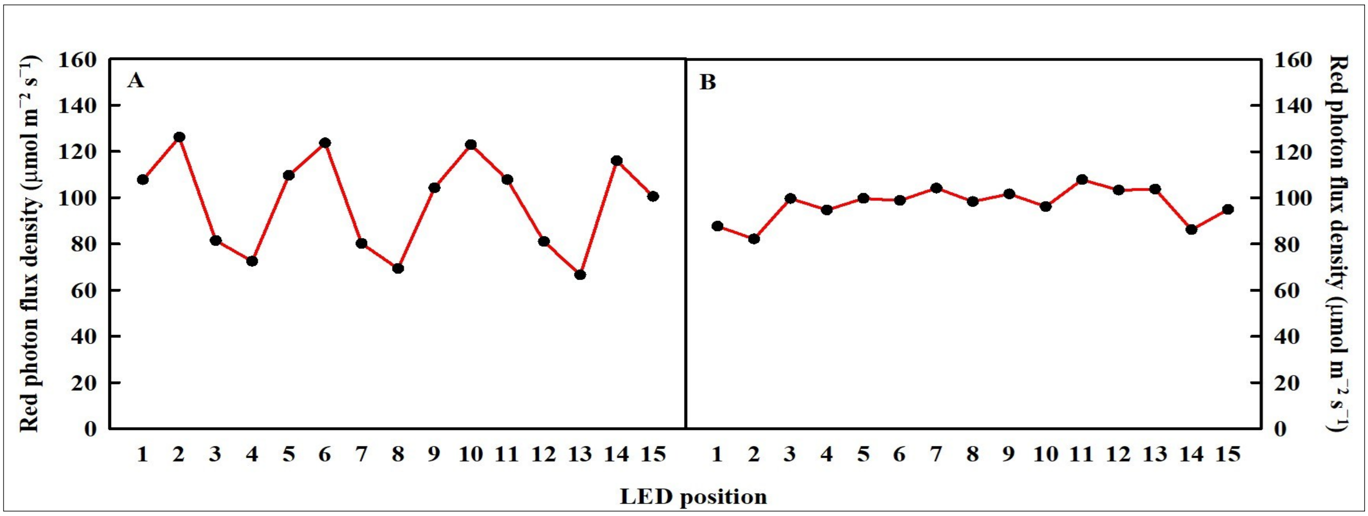

Fig. 4. The light distribution of the 2W4R (**A**) and 1W8R (**B**) treatments in the cultivation area for kale under the location of the red chips. The points from 1 to 15 indicate positions from left to right on the LED bar. Each point is located on a vertical line between the LED bar and the cultivation bed.

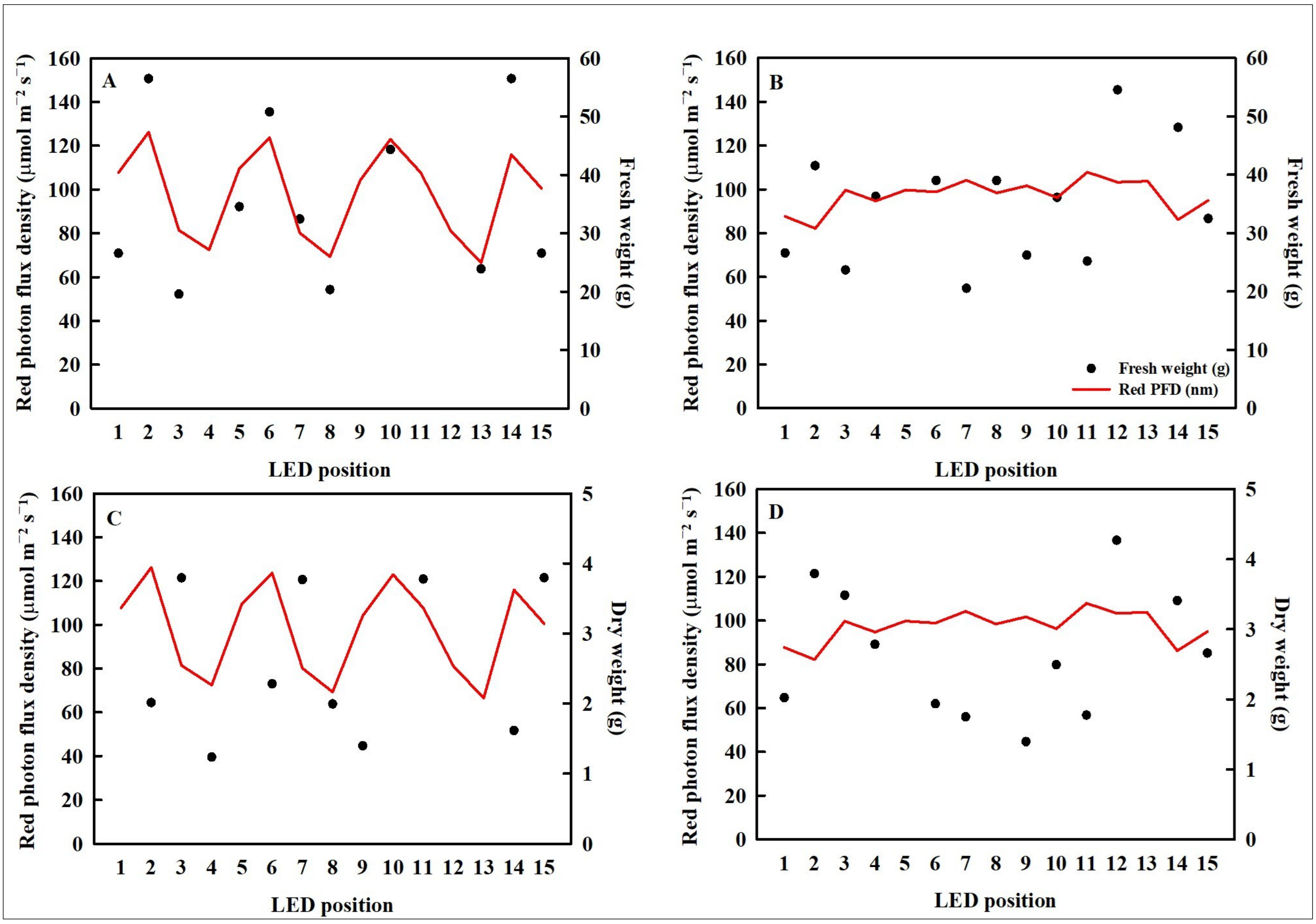

Fig. 5. Correlation between kale biomass and the red-light distribution of the LED bar in the 2W4R (**A**, **C**) and 1W8R (**B**, **D**) treatments. Kale fresh weight (**A**) and dry weight (**C**) in the 2W4R treatment, and kale fresh weight (**B**) and dry weight (**D**) in the 1W8R treatment. The points represent the plant biomass of kale grown at each location and the red line represents the measured red photon flux density at each location.

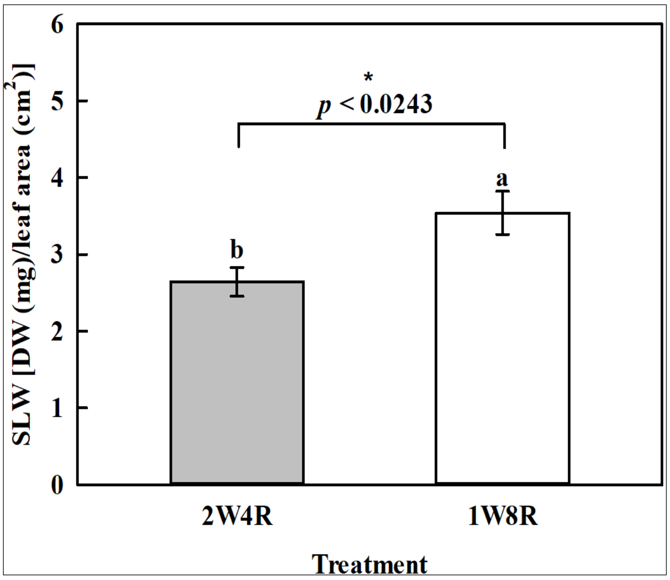

Fig. 6. The leaf thickness index of kale exposed to different light sources (*n* = 6). Statistically significant differences were identified using Duncan's multiple-range test. * is $p < 0.05$, DW is Dry weight.

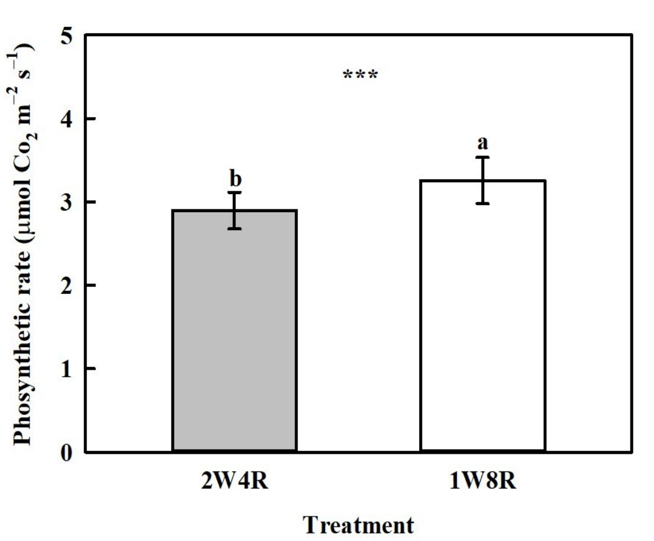

Fig. 7. The photosynthetic rate of kale exposed to different light sources (*n* = 8). Statistically significant differences were defined at $p < 0.05$ in Duncan's multiple-range test. *** is $p < 0.001$. Different letters indicate statistical differences between the treatments.

The light distribution, determined by the density of the red LED chips, had a significant effect on kale photosynthesis (Fig. 7). The photosynthetic rate of kale increased by 30.9 % under the 1W8R treatment compared with that under the 2W4R treatment.

Discussion

The cost of an LED chip correlates with its wattage, becoming more expensive as the wattage increases and less expensive as it decreases. Utilizing multiple low-wattage LED chips to achieve an equivalent wattage can be more cost-effective than using a single high-wattage LED chip. Furthermore, the dense placement of low-wattage LED chips enables uniform light exposure for the plants. In vertical farming, light is a crucial component and the initial installation cost of the predominantly used LEDs is considerable, making cost-effective LED design paramount. Therefore, we compared the crop production capabilities of LEDs with varying wattages and identical power consumption.

Red light distribution was analyzed to investigate the effect of red irradiance uniformity on plant growth. The uniformity of the light emitted by LEDs depends on the location and distribution of each LED chip (37). Additionally, the ratio of each spectral component in LED light can positively affect plant growth and is a crucial consideration in LED light design (38). Another study reported that even if the PPFD distribution on the growing surface is uniform (39), the PPFD distribution in the plant canopy may not be uniform. Properly adjusting the arrangement of lamps can achieve a uniform light distribution across the plant canopy. In this study, different arrangements of red chips were designed to focus on the effects of red light, which is an important wavelength for plant growth (40).

In the 2W4R configuration, the red PPFD was high in areas under the red LED chips and low in areas without them, resulting in a non-uniform red light distribution. This differential light distribution caused the baby leaf soybean plants to grow faster in length only in areas where the red light was concentrated. It was also reported that red light improves plant height and our study supports this finding, as the height of baby leaf soybean plants increased due to greater amounts of red light at positions with a higher red PPFD (24). In contrast, soybean plant height was uniform under the 1W8R treatment. A study demonstrated that when chrysanthemums were grown with LEDs whose beam angles could be adjusted for uniform light distribution (41), they showed a more uniform plant height than when grown with conventional LEDs. The temperature of the cultivation bed was higher in areas with red chips than in areas with white chips, although the average temperatures were the same for 2W4R and 1W8R. During the experimental period, the heat emission from the LEDs caused the ambient temperature around the high-wattage LED (2W4R) treatment group to be approximately 1 °C higher than that of the low-wattage (1W8R) group, affecting both the LED and plant surroundings. Higher wattage LEDs require more energy and emit more heat than lower wattage LEDs, which affects the temperature of the plant (42). The above results indicate that the higher radiant heat of the 2 W red chips led to uneven plant growth and production in certain areas under the red chips. Therefore, when designing LED systems, the effect of the heat emitted by the LED chips on the temperature of the cultivation environment should be considered.

The STI refers to the height of a plant with the same amount of dry matter, with a lower STI indicating a thicker stem (31). In the present study, the STI of the 1W8R treatment group was higher than that of the 2W4R treatment group, suggesting that uniform light distribution strengthened the stems of baby leaf soybean plants. Thick hypocotyls are crucial for baby leaf soybean production, facilitating rapid water absorption and higher yields (43). Plants accumulate over 90 % of their biomass through photosynthesis (44), which occurs more efficiently when all leaves received uniform light intensity, rather than varying intensities among individual leaves (45). Therefore, the more compact stem growth observed in the 1W8R treatment group in our study was likely the result of densely arranged low-power red LED chips. This arrangement exposed the entire plant to uniform light intensity, thereby enhancing photosynthesis and increasing biomass accumulation.

The SLW represents the DW per leaf area of the plant, with a larger value indicating a thicker leaf and more compact leaf structure. Thicker leaves are positively related to abundant harvest production, signifying higher biomass (46). In this study, leaf thickness became compact with a high SLW in the 1W8R treatment group, which received uniform light. This could be a mechanism similar to the effect of enhanced biomass accumulation owing to uniform light irradiation, as evidenced by the uniform thickness of baby leaf soybean stems.

Leaves with compact structures have a positive relationship with photosynthesis, and since photosynthesis is closely related to the production of plant biomass, it can be used to evaluate crop quality. A study demonstrated a positive correlation between the SLW of alfalfa plants and the net photosynthesis rate (35). Leaves with a dense structure can be positively correlated with the rate of photosynthesis because they have a higher concentration of chlorophyll, which captures light energy and more abundant nitrogen, which is involved in the metabolic processes related to photosynthesis (47). Therefore, the increase in the SLW of kale under the 1W8R treatment could be a result of greater biomass accumulation due to a higher rate of photosynthesis. This study confirmed the positive effect of uniform light distribution on the production of high-quality crops, such as baby leaf soybean and kale, by improving the thickness and hardness of the leaves, which are important factors for the commercialization of crops.

Photosynthesis is powered by light (48) and the rate of photosynthesis directly influences the efficiency of the process. In the present study, the photosynthetic rate of kale grown under LEDs with an even red light distribution was high. During the cultivation period, as the leaves of kale grew and the distance between the plant and LED chips decreased, the red light irradiated on the kale was uniformly absorbed, possibly increasing the photosynthetic rate (49). Additionally, a higher diffused light rate reduces canopy air and leaf temperatures, thereby promoting photosynthesis in tomato plants (50). These results are similar to our research results, which showed that the air and leaf temperatures of the kale canopy decreased during the cultivation period under LEDs with more densely placed 1 W red chips.

In addition, a study reported a positive correlation between SLW and net photosynthetic rate (35). In the present study, the SLW of kale was significantly higher in the treatment with densely arranged red chips with low power consumption than in the other treatment, which is thought to be related to an increase in the net photosynthetic rate. However, further research is needed on the correlation between SLW and net photosynthesis rate in kale. Furthermore, while yield and nutritional quality are essential factors in producing high-quality crops, this study only investigated the growth characteristics of baby leaf soybean and kale under uniform light distribution. Therefore, additional analyses of various metabolites and minerals, such as isoflavones and glucosinolates, which are the main substances in baby leaf soybean and kale, are needed.

Conclusion

This study examined the effects of different LED designs on the growth of baby leaf soybean and kale, focusing on the uniformity of PPFD distribution within cultivation areas. The 1W8R treatment showed a more positive impact on both the uniformity of the PPFD and the growth of baby leaf soybean and kale. The findings suggest that non-uniform red light distribution can negatively affect plant production in vertical farms, even if the average PPFD is the same. Using 1W red LED chips instead of 2W chips was found to enhance crop yield and enables stable production through uniform crop growth in vertical farms. This study serves as a valuable reference for optimizing the lighting design to achieve uniform red lighting distribution and lower costs in commercial vertical farming systems.

Acknowledgements

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Authors' contributions

SNJ and MJK conceptualized the study, developed the methodology, conducted formal analysis, performed investigation and data curation and prepared the original draft; HSS, GOL, YLK, DYC, JGJ, MJK, JBJ and HYL contributed to data curation, formal analysis, investigation and methodology; while SK, JHK, YP, KMC and KHS supervised, validated, acquired funding and reviewed and edited the manuscript, with all authors approving the final version.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

Supplementary data

Table S1. Hogland nutrient solution components used in this study.

Table S2. Peak wavelength and spectral ratio of each light source.

Fig. S1. The thermal images of 2W4R (A) and 1W8R (B) treatments and temperature for cultivation location (C) for 3 days. Statistically significant differences are detected at $p < 0.05$ in Duncan's multiple range test. Different letters indicate statistical differences between the treatments.

Fig. S2. Appearance diagram of the experimental cultivation area. Picture of the experimental site of vertical farming used in this study (A), the diagram of cabinets used to grow the plants (B) and the diagram of 1 cabinet (C), which includes the points of measured PPFD.

Fig. S3. The diagram of 2W4R (A) and 1W8R (B) with 15 light measuring points. The red point indicates the point immediately below the red chip and the yellow point indicates a certain point between the red chips.

Fig. S4. Simulation of light distribution of cultivation shelves to different light sources. Simulation of light distribution in 2W4R (A-D),1W8R (E-H) and distribution of PPFD (A, E), a real color view (B, F), CCT chart (C, G) and Kelvin (D, H).

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