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# Evaluation of Light Intensity and Uniformity of LEDs for Protected Crop Production

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**Abstract** This study was conducted to evaluate light intensity and uniformity of two SMD (surface-mount device) type LEDs for protected crop production. A low-power (0.1 W) and a high-power (1 W) LEDs were selected and the intensity and uniformity was evaluated at different vertical (height) and horizontal (distance) intervals. When the horizontal interval of the LED bar was fixed, the light intensity increased and the uniformity decreased as the height decreased. At the 30~40 cm heights, 20~30% of the area showed 200 ±20 $\mu$molm$^{-2}$s$^{-1}$. As the horizontal distance of the LED bars increased, while the uniformity increased as well, the light intensity decreased. At the distances of 6~10 cm, 17~23% of the area showed 200 ±20 $\mu$molm$^{-2}$s$^{-1}$. When the LED bars were added to the sides, the light intensity and uniformity were generally improved. Results showed that the light intensity and uniformity depended on the height and interval of the LED bulbs; therefore, optimum arrangement for the crops interested should be determined through experiments.

**Keywords** Protected production, LED, Light intensity, Uniformity

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## 1 Introduction

As the world population and the uncertainty of food production due to climate change increase, the interest concerning the protected crop production including the greenhouse and plant factory has increased for a stable food production receiving the minimum effect of the external climate. Protected crop production enables year-round production through environmental management, and has an advantage to control the quantity and quality of the crops. Because a greenhouse or a plant factory cannot use sunlight directly, it is very important to secure the light required for the crop growth.

In the protected crop production, to secure enough light for the crop production, the artificial lights such as a high-pressure sodium lamp, metal halide lamp, the fluorescent lamp, and LED (light emitting diode lamp) are used. Among these, because the LED lamp has a narrow width of wavelength, can select a particular wavelength, and is applied in a relatively small space by miniaturizing the lighting product, it is used diversely as a lighting source for the protected crop production.

Plants receive the energy from the light and grow by photosynthesis and respiration. The optimum light wavelength and intensity are different depending on each crop. While the various types of LEDs are used currently in the protected crop production, the suitability of the light intensity and the uniformity for the plant cultivation need to be evaluated. As described above, in case of producing a light source in the protected crop production, it is important to know whether the light intensity is secured or not and whether the intensity is even or not. The purpose of this study is to evaluate the light intensity and uniformity according to the types and placements of the LED bulbs used frequently in the current protected crop production.

## 2 Literature Review

Among the lamps used in the protected crop production, it is difficult to use a high-pressure sodium lamp in the plant factory with the multi-step producing facility because it generates a large quantity of heat so that enough distance from the plants is maintained; a high-pressure sodium lamp and a metal halide lamp have a large amount of electric power consumption and an insufficient light utilization efficiency due to the shortage of the blue and red lights used for the plant photoreaction (Kim and Lee, 1998). The LED lamp can be used in a relatively narrow space because it has a narrow wavelength width, can select a specific wavelength, and can be miniaturized. Additionally, it consumes a low amount of electric power and has a semi-permanent life expectancy. By the LED technology development, it can be applied to the different types of crops, and the production power is increased by controlling the light source appropriate to the characteristics of a specific crop. It can be operated with a low voltage due to its high reliability and responsibility. As an advantage of this, a pulse investigation that is beneficial for the photosynthesis is possible (Kim, 1999). Particularly, the research on green vegetables is actively conducted, and it is expanding to the area of a crop for a special purpose.

Plants receive energy by light and grow through the photosynthesis and respiration. According to the photoperiod and photosynthetic photon flux (PPF), the vegetative growth and reproductive growth were affected; according to the wavelength, the growth is different (Fankhauser and Chory, 1997). Plants photosynthesize in the range of 380~760 nm including the visible light range. Here, the radiant energy of the wavelength range in which photosynthesis occurs is called the photosynthetically active radiation (PAR); its unit is $W \cdot m^{-2}$, and it is used when the light intensity is expressed as energy; the PPF is used as an index of the quantity of light that is effective for photosynthesis. The unit of PPF is expressed as $\mu mol \cdot m^{-2} \cdot s^{-1}$.

The proper light range and PPF size were different for each crop. As a result of estimating the optimum cultivation environment of lettuce through the photosynthesis efficiency model, it was reported that the photosynthesis velocity was high at more than $200 \mu mol \cdot m^{-2} \cdot s^{-1}$ of PPF (Kim et al., 2004). Hong et al. (2010) investigated the mixed light in the closed environment to review the effect in lettuce growth. As a result of the evaluation after manufacturing by adding two blue LEDs with 470 nm for each of the 20 red LEDs within the 660 nm range, the blue light ratio increased, and the biomass increased as well; therefore, it was verified that the plant cultivation using a mixed light of red and blue LEDs in the closed environment was effective.

Hwang et al. (2013) found the even placements by analyzing through the simulation result about the illumination intensity distribution and uniformity as well as the illumination intensity distribution depending on the height. As a result of analyzing the simulation values, it was drawn that the wavelength required in the plants were 660 nm of red and 450 nm of blue; it was verified that if these lights are mixed in a 3:1 ratio, they become the LED for plant cultivation through the spectrum result or the light absorption result of the chloroplasts a and b.

Using the illumination designing program, Lee et al. (2012) analyzed the illumination intensity distribution and the uniformity of each cultivation bed according to the arrangements of the height and interval of the LED illumination system as well as the changes of the overall energy consumption through the simulation. As an actual measurement value of the illumination intensity of the plant cultivation beds through the potable illumination intensity measuring device, the 801(lx)~1,864(lx) range of the illumination intensity distribution was shown, and the 1,367(lx) of the average illumination intensity and the 1:1.71 ratio of uniformity were verified. As a result of conducting the simulation of the plant cultivation beds under the same conditions, the illumination intensity distribution with the value, which is close to the actual measurement value of 828(lx)~1,850(lx), was shown; the average illumination intensity and the uniformity were respectively 1,400(lx) and 1:1.69 with trivial error.

Han et al. (2011) suggested the ultrasonic sensor based LED lighting control system structure to figure out the distance between the plants and the lamp according to the plant growth speed using the ultrasonic distance measuring sensor. After installing the showcase typed Mini Plant (140x150x80 cm) consisting of two beds for the experiment, the bar typed LED manufactured with the 11:7 ratio of red and blue wavelengths and the controller to manage this were attached to the top part of each cultivation bed. The PPFD averages of the second and third rows among the four rows of the cultivation beds showed a higher result than the averages of the first and third rows; according to the lighting and the height of the plants, the PPFD averages also showed a high distribution in each row as their interval became narrower. If the height between the lighting and plants is properly adjusted according to the plant type and its growth speed, it could be expected that the energy consumption rate would be improved by the lighting.

Ferentino and Albright (2004) developed the algorithm technology for the optimum design of the illumination system of the greenhouse crop production business. The experiment about the installation height according to the electricity capacity of lighting was conducted by installing 250, 400, 600, 1000 W of illumination system on each of the 2.5, 3.0, 3.5, 4.0 of the installation heights. As a result of the light quantity measurement, it was possible to apply to the system on the 3~3.5m heights, and it was thought that the cost reduction of the protected crop production could be possible according to the installation height.

## 3 Materials and Methods

### 3.1 LED and Light Quantity Measurement Device

The light quantity related to plant photosynthesis is expressed as a unit of photosynthetic photon flux (PPFD) in general. The optimum PPFD is different depending on each plant; in major crops, the light saturation points of tomato /watermelon, lettuce, orchid kinds, and ginseng were respectively 843 $\mu mol \cdot m^{-2} \cdot s^{-1}$, 302 $\mu mol \cdot m^{-2} \cdot s^{-1}$, 121 $\mu mol \cdot m^{-2} \cdot s^{-1}$, and 145 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (Lee, 2010). Through the production environment optimization experiment of the plant production system using the photosynthesis efficiency model, it was verified that the lettuce growth was best at more than 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of PPF (Kim et al., 2004). In the study with consideration of the light saturation point of the general green vegetables and the PPF of the lettuce growth, the light intensity of the LED was measured by targeting the light quantity of the 220 $\mu mol \cdot m^{-2} \cdot s^{-1}$ level.

In this study, the experiment was conducted by selecting each kind of LED from a low-power (0.2 W class) and a high-power (3 W class) of the Surface Mounted Devices (SMD) type. A low-power LED was arranged by blue (450~480 nm), red (630~650 nm), and white (400~750) LEDs of the 11:4:3 ratio (Model: SMD 2835, Shenzhen LP Technology Co., Ltd., China). A high-power LED was arranged by blue (430~440 nm), red (630~660 nm), and white (400~750) LED of the 11:4:3 ratio (Model: PGL-PFL, PARUS Co., Ltd, China). The SMD-typed LED can be used in the general Printed Circuit Board (PCB) because it is easy to purchase and to do a soldering work comparing to the other types of LEDs. Additionally, there is an advantage in doing the interval control and arrangement relatively free.

In the crop cultivation, the light quantity has an effect to the photosynthesis activity, etc. The light quantity can be calculated by multiplying the light velocity and time, and the light velocity refers to the light energy passing through a certain surface during the unit time. In this study, the PPF measurement device (Model: MQ-200, Apogee instruments Inc., Logan, Utah, USA) was used. In the state of maximally blocking out the surrounding lights, the average value was used by measuring three times per point for five seconds.

### 3.2 Experimental Equipment and Methods

The experimental equipment manufactured in this study consisted of a bench and a cultivation bed. The bench consisted of a width of 90cm, a length of 60cm, and a height of 100cm, and on the top part, it was designed so that LED can be installed within the interval. Additionally, it was manufactured to load the cultivation bed at every 10cm of height. The light quantity was measured at the total of 70 points with 10cm intervals of each width and length in the area of the cultivation bed with the 90cm of width and 60cm of length.

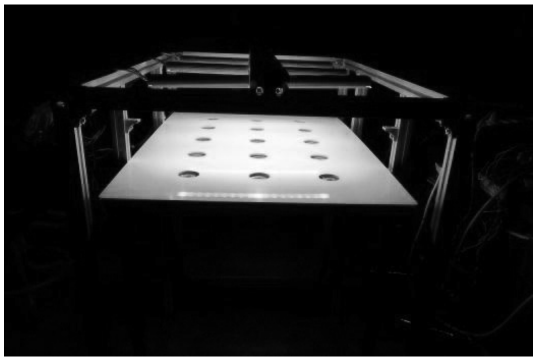

**Fig. 1** Constructed experimental bench showing the LED installation frame and cultivation bed.

The measurement method depending on the LED height was performed with the total of seven heights in 10~70cm by changing the height of the LED bar every 10cm from the cultivation bed. It was established based on the green vegetables with 40~50cm of length. The uniformity refers to the ratio of each measurement point of the illumination intensity. Although there are many kinds of uniformity calculation methods, the methods suggested by the Commission International de L'Eclairage (CIE) etc. including U=Min/Ave or U=Min/Max (U=uniformity, Ave=average illumination intensity (lx), Min=minimum illumination intensity (lx), Max=maximum illumination intensity (lx)) were used (Kim and An, 1999). In this study, the uniformity was calculated by dividing the minimum value with the average value.

The LED measurement method depending on the intervals was performed by fixing the LED bar height to 40cm, widening the interval of a high-power LED bar every 5cm up to 10~30cm, and widening the interval of a low-power LED bar every 2cm up to 4~12cm.

## 4 Results and Discussion

### 4.1 Light intensity and uniformity by the vertical height

The measurement results about a high-power LED in each height were presented in Table 1 and Figure 2. When the light source lamps are at the height of 20 and 30cm from the cultivation bed, the light quantity level of 200±20 was distributed in the largest area as 30 and 15% of the overall cultivation bed area. As the height increased, the light intensity decreased although the uniformity increased. When the height was 10 cm, the average value of the light quantity was the highest at 170 and the uniformity value was the lowest. The average values of the light quantity were 161 at 20cm, 139 at 30cm, 118 at 40cm, 77 at 60cm, and 66 at 70cm of height.

**Table 1** Summary of the light intensity (PPFD, μmol·m$^{-2}$·s$^{-1}$) and uniformity (%) by height for the high-power LEDs.

| Height, cm | PPFD | | | Uniformity, % |
|---|---|---|---|---|
| | Avg. | Max. | Min. | |
| 10 | 170 | 652 | 3 | 1.76 |
| 20 | 161 | 415 | 12 | 7.45 |
| 30 | 139 | 308 | 29 | 20.86 |
| 40 | 118 | 227 | 39 | 33.05 |
| 50 | 94 | 156 | 44 | 46.81 |
| 60 | 77 | 116 | 43 | 55.84 |
| 70 | 66 | 89 | 41 | 62.12 |

**Table 2** Summary of the light intensity (PPFD, μmol·m$^{-2}$·s$^{-1}$) and uniformity (%) by height for the low-power LEDs.

| Height, cm | PPFD | | | Uniformity, % |
|---|---|---|---|---|
| | Avg. | Max. | Min. | |
| 10 | 153 | 384 | 7 | 4.58 |
| 20 | 136 | 309 | 13 | 9.56 |
| 30 | 119 | 245 | 24 | 20.17 |
| 40 | 104 | 200 | 30 | 28.85 |
| 50 | 92 | 165 | 34 | 36.96 |
| 60 | 82 | 132 | 36 | 43.90 |
| 70 | 71 | 106 | 33 | 46.48 |

The measurement results about a low-power LED in each height were presented in Table 2 and Figure 3. At the 30 and 40cm of height, the light quantity level of 200±20 $\mu$molm$^{-2}$s$^{-1}$ was distributed most widely as 24 and 25%. While the average value of the light quantity was the highest as 153 at 10cm of height, the uniformity value was the lowest. The average values of the light quantity were lowest as 136 at 20cm, 119 at 30cm, 104 at 40cm, 92 at 50cm, 82 at 60cm, and 71 at 70cm of height, and the light uniformity was measured the highest. When comparing to the high-power LEDs, the light quantity and uniformity were somewhat low.

By additionally installing the LEDs at both ends of the cultivation bed, the results of measuring the light quantity and light uniformity in every height were summarized in Table 3. Although the average value of the light quantity did not show a big difference, the uniformity improved by 50% in a high-power LED and by 40% in a low-power LED. Therefore, it was verified that the uniformity can be improved by additionally installing LEDs.

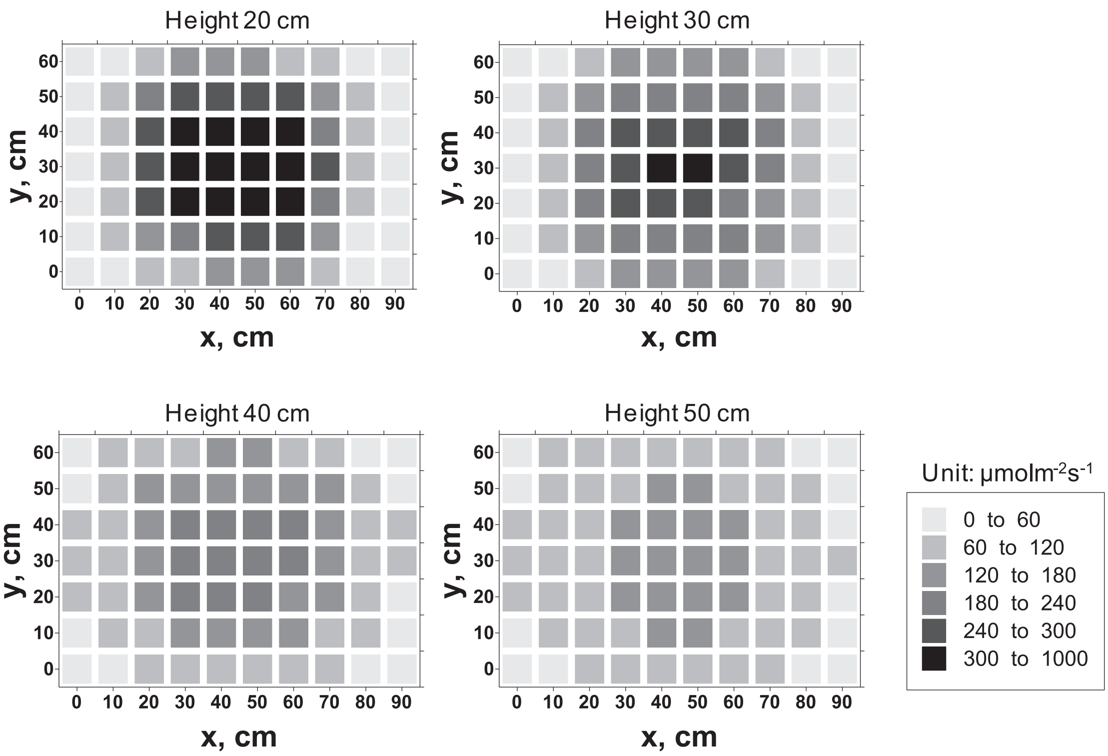


**Fig. 2** Spatial distribution of the light intensity (PPFD, μmol·m$^{-2}$·s$^{-1}$) by height for the high-power LEDs.

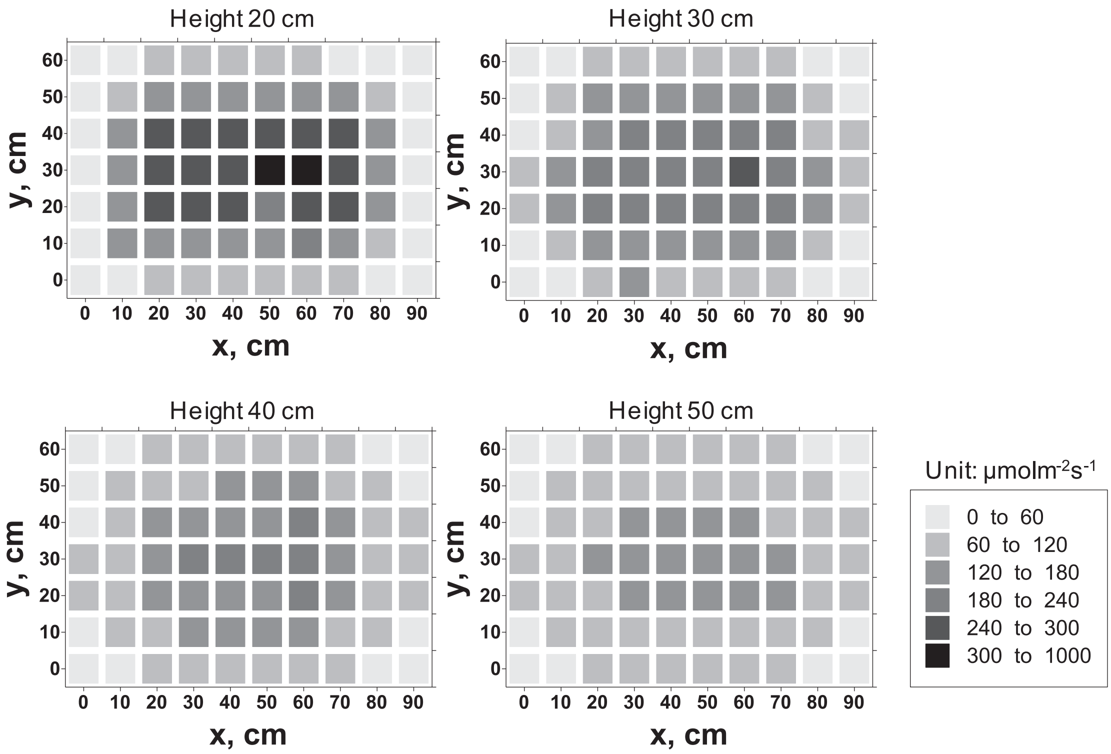


**Fig. 3** Spatial distribution of the light intensity (PPFD, μmol·m$^{-2}$·s$^{-1}$)) by height for the low-power LEDs.

**Table 3** Summary of the light intensity (PPFD, μmol·m$^{-2}$·s$^{-1}$) and uniformity (%) by height for the LEDs with additional LED bars at the sides.

| LED | Height, cm | PPFD | | | Uniformity, % |
|---|---|---|---|---|---|
| | | Avg. | Max. | Min. | |
| High power | 10 | 283 | 623 | 42 | 14.84 |
| | 20 | 190 | 294 | 79 | 41.58 |
| | 30 | 143 | 213 | 74 | 51.75 |
| | 40 | 108 | 151 | 68 | 62.96 |
| | 50 | 83 | 109 | 59 | 71.08 |
| | 60 | 65 | 80 | 50 | 76.92 |
| | 70 | 52 | 62 | 42 | 80.77 |
| Low power | 10 | 186 | 382 | 17 | 9.14 |
| | 20 | 138 | 265 | 41 | 29.71 |
| | 30 | 116 | 209 | 39 | 33.62 |
| | 40 | 103 | 152 | 42 | 40.49 |
| | 50 | 94 | 114 | 39 | 41.49 |
| | 60 | 82 | 85 | 39 | 47.56 |
| | 70 | 71 | 64 | 38 | 53.52 |

### 4.2 Light intensity and uniformity by the horizontal distance

The measurement results regarding a high-power LED in each horizontal interval were presented in Table 4 and Figure 4. By changing the LED bar interval every 5 cm and fixing the measurement height to 40cm, the light quantity was measured. As a result of this, when the interval was 10cm, the light quantity of 200±20 $\mu$molm$^{-2}$s$^{-1}$ was distributed most widely as 23%. While the average value of the light quantity was the highest as 119 at the 10cm of interval, the uniformity was the lowest. The average values of the light quantity were lowest as 115 in 15cm, 112 in 20cm, 108 in 25cm, and 103 in 30cm of interval, and the light uniformity was measured as the highest.

**Table 4** Summary of the light intensity (PPFD, μmol·m$^{-2}$·s$^{-1}$) and uniformity (%) by distance for the high-power LEDs.

| Distance, cm | PPFD | | | Uniformity, % |
|---|---|---|---|---|
| | Avg. | Max. | Min. | |
| 10 | 119 | 252 | 34 | 28.57 |
| 15 | 115 | 222 | 37 | 32.17 |
| 20 | 112 | 195 | 41 | 36.61 |
| 25 | 108 | 175 | 44 | 40.74 |
| 30 | 103 | 160 | 49 | 47.57 |

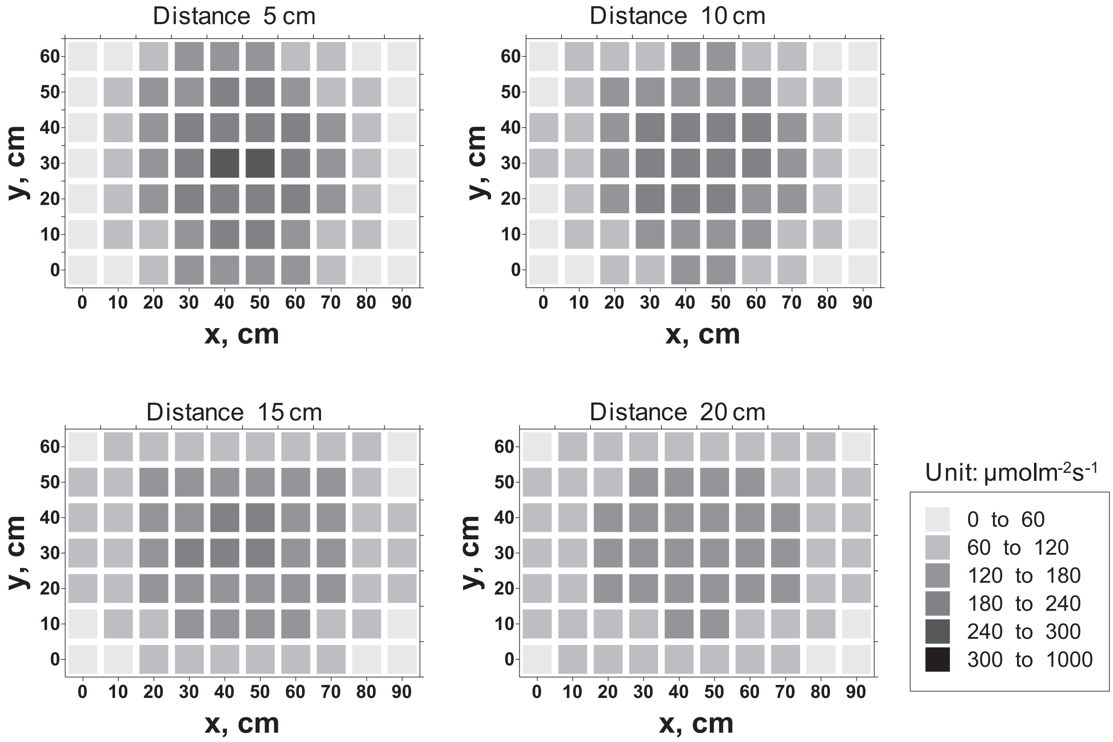


**Fig. 4** Spatial distribution of the light intensity (PPFD, μmol·m$^{-2}$·s$^{-1}$) by distance for the high-power LEDs.

The measurement result regarding a low-power LED in each horizontal interval was presented in Table 5 and Figure 5. By changing the LED bar interval with 2cm and fixing the measurement height to 40cm, the light quantity was measured. When it was 6cm in the result, the light quantity of 200±20 $\mu$molm$^{-2}$s$^{-1}$ was distributed most widely as 17%. When the interval was 6cm, although the average value of the light quantity was the highest as 108, the uniformity was low. When the interval was 4cm, the average value of the light quantity was 100; when the interval was 8cm, it was also measured as 100. When the interval was 10cm, it was 102; when the interval was 12cm, it was the lowest as 94, and the light uniformity was measured as high. The light uniformity was measured the highest when the interval was 10cm.

**Table 5** Summary of the light intensity (PPFD, μmol·m$^{-2}$·s$^{-1}$) and uniformity (%) by distance for the low-power LEDs.

| Distance, cm | PPFD | | | Uniformity, % |
|---|---|---|---|---|
| | Avg. | Max. | Min. | |
| 4 | 100 | 262 | 14 | 14.00 |
| 6 | 108 | 255 | 18 | 16.67 |
| 8 | 100 | 206 | 25 | 25.00 |
| 10 | 102 | 183 | 35 | 34.31 |
| 12 | 94 | 160 | 29 | 30.85 |

The measurement results of the light quantity and light uniformity in every interval by additionally installing LEDs in both ends of the cultivation bed were summarized in Table 6. The results show that although the average value of the light quantity did not show a big difference like the experiment depending on each height, the light uniformity increased by 42% in a high-power LED and 47% in a low-power LED.

**Table 6** Summary of the light intensity (PPFD, μmol·m$^{-2}$·s$^{-1}$) and uniformity (%) by distance for the LEDs with additional LED bars at the sides.

| LED | Distance, cm | PPFD | | | Uniformity, % |
|---|---|---|---|---|---|
| | | Avg. | Max. | Min. | |
| PGL-PFL (PARUS) | 10cm | 112 | 163 | 60 | 53.57 |
| | 15cm | 108 | 151 | 68 | 62.96 |
| | 20cm | 96 | 128 | 62 | 64.58 |
| | 25cm | 86 | 113 | 57 | 66.28 |
| | 30cm | 77 | 100 | 52 | 67.53 |
| SMD type LED | 4cm | 112 | 183 | 48 | 42.86 |
| | 6cm | 111 | 185 | 52 | 46.85 |
| | 8cm | 92 | 152 | 42 | 45.65 |
| | 10cm | 93 | 151 | 45 | 48.39 |
| | 12cm | 91 | 149 | 45 | 49.45 |

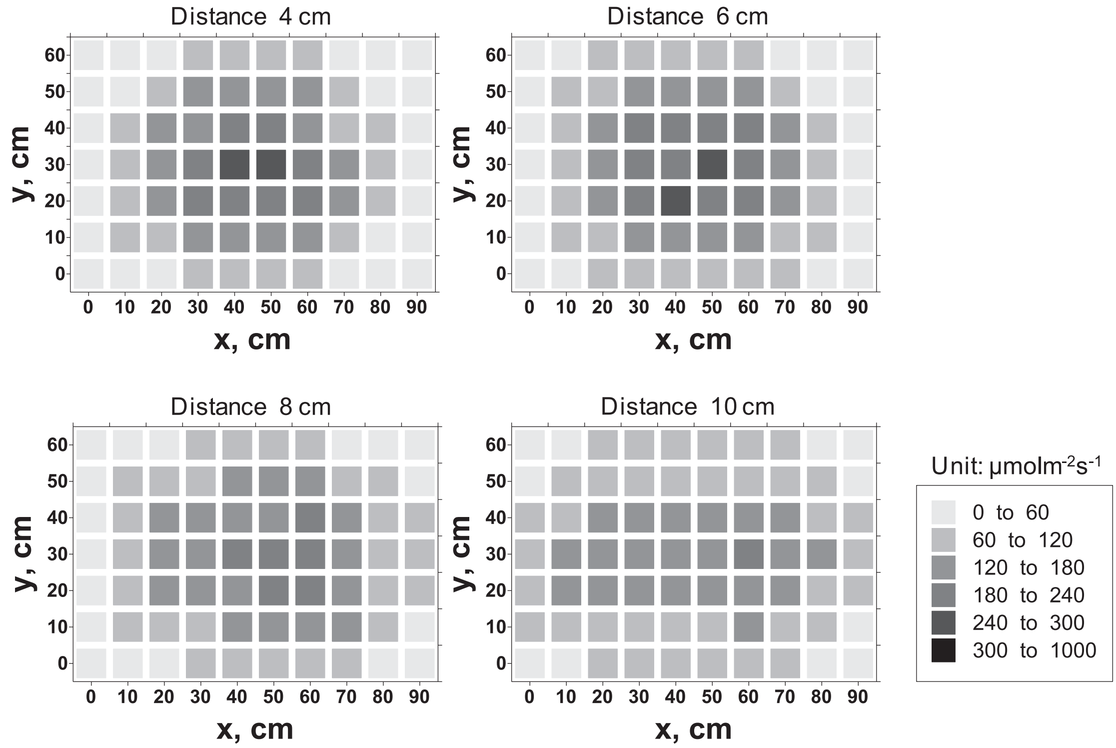


**Fig. 5** Spatial distribution of the light intensity (PPFD, $\mu mol \cdot m^{-2} \cdot s^{-1}$) by distance for the low-power LEDs.

## 5 Summary and Conclusions

This study was conducted to evaluate the light quantity and the uniformity depending on each height from the crop and interval of the LED bars about the two types of LEDs used frequently as light sources in the protected crop production. The LEDs were selected from each of the high-power and low-power. The main results are as follows:

1) As the height of the light source lamp increased from the cultivation bed, the light intensity decreased although the uniformity increased. As a result of measuring a high-power LED depending on the height, at the 20 and 30cm of height, the light quantity level of 200±20 $\mu molm^{-2}s^{-1}$ was distributed in the widest area. Although the average value of the light quantity was the highest as 170 at the 10cm of height, the uniformity was the lowest. As a result of measuring a low-power LED depending on the height, the light quantity level of 200±20 $\mu molm^{-2}s^{-1}$ was distributed in the widest area as 24 and 25% at 30 and 40cm of height. Although the average value of the light quantity was the highest as 153 at 10cm of height, the uniformity was the lowest. When comparing to the high-power LEDs, the light quantity and the uniformity were somewhat low. As a result of measuring the light quantity and light uniformity in each height by additionally installing LEDs at the both ends of the cultivation bed, while the average value of the light quantity did not show a big difference, the uniformity was improved by 50% in a high-power LED and 40% in a low-power LED.

2) As a result of measuring the LED bar in each horizontal interval, for the high-power LEDs, the light quantity of 200±20 $\mu molm^{-2}s^{-1}$ was most widely distributed as 23% in the 10cm of interval. While the average value of the light quantity was the highest as 119 in 10cm of interval, the uniformity was the lowest. As a result of measuring the low-power LED depending on each interval, the light quantity of 200±20 $\mu molm^{-2}s^{-1}$ was most widely distributed as 17% in 6cm of interval. While the average value of the light intensity was the highest as 108 in 6cm of interval, the uniformity was low. As a result of measuring the light quantity and the light uniformity in each interval by additionally installing LEDs in the both ends of the cultivation bed, the average light quantity did not show a big difference like the result of the experiment depending on each height; however, the light uniformity of a high-power LED increased by 42%, and the light uniformity of a low-power LED increased by 47%.

In this study, it was verified that the light intensity and the uniformity were seriously affected by the formation of the LED bar, the interval of the light source, and the distance from the light source. It was also confirmed that crops can have a necessary light intensity from the commercial LEDs. The optimum conditions about the proper interval and distance of the LED light source depending on each crop cultivated should be decided through the experiment.

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