A THESIS FOR THE DEGREE OF MASTER OF SCIENCE

3D Plant Model-based Estimation of Light Interception and Photosynthetic Rate of Lettuces Grown under LEDs in Plant Factory

3 차원 식물모델을 이용한 LED 식물공장 재배 상추의 수광량 및 광합성 속도의 예측

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3D Plant Model-based Estimation of Light Interception and Photosynthetic Rate of Lettuces Grown under LEDs in Plant Factory

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ABSTRACT

In plant factories, light use efficiency (LUE) should be improved to reduce electrical cost. To evaluate LUE, light interception should be estimated under different lighting conditions. The objective of this study was to estimate the light interception, photosynthetic rate, and LUE of lettuces grown under LEDs. 3D-scanned plant models and ray-tracing simulation were used to estimate the light interception. Canopy photosynthetic rate was estimated by modified Farquhar-von, Caemmerer-Berry (FvCB) model based on simulation result. To analyze the accuracy, measured light intensities and canopy photosynthetic rates in a growth chamber with LEDs were compared with simulated values. Under several scenarios, changes in light interception under different light environments were analyzed. Light intensities and canopy photosynthetic rates obtained by simulation showed good agreements with measured ones. Canopy light distribution was affected by planting distance, but whole light interception was almost similar. The canopy light interception was gradually increased with decreasing lighting distance, but rather decreased at too intact lighting due to heterogenetic light distribution. With high floor reflectance, canopy light interception was more increased at larger planting distance. It was confirmed that this method could quantify the light environments and photosynthetic rate at various electrical light conditions and is useful tool to estimate LUE in plant factories.

Additional key words: light use efficiency (LUE), ray-tracing simulation, Farquhar-von, Caemmerer-Berry (FvCB) model, lighting distance, reflectance

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INTRODUCTION

Plant factories are able to precisely control various environmental factors that affect growth and yield of plants, enabling stable year-round production with high productivity and quality (Kozai et al., 2005). The most distinctive feature of plant factories compared with outdoor or greenhouse cultivation is the use of electrical light sources. However, electrical energy consumption is one of the major drawbacks for operating commercial plant factories. Electrical energy occupies the largest part of operation cost of plant factories and most of electrical energy consumption derives from lighting rather than other energy loads, such as heating, cooling and dehumidification in plant factories (Ohyama, 2015; Graamans et al., 2018). Nevertheless, the strength of plant factory is full control of light environments by changing lighting factors such as spectrum, intensity, disposition, and distribution. For improving light efficiency, several lighting strategies were tried, such as supplementary light from underneath (Zhang et al., 2015), targeted lighting on canopy (Poulet et al., 2014), and usage of optical equipment (Li et al., 2016), which achieved the higher light use efficiency or electricity use efficiency. In general, the effect of lighting method is evaluated with crop growth or yield, but requires lots of times, labors and costs for the experiments.

If light interception of plant canopy and light use efficiency of plant canopy can be estimated under specific light environments without cultivation, the optimized lighting strategy can be designed with saving time and resources. Moreover, potential photosynthetic rate and growth can be estimated by photosynthesis and growth model. But because of the technical limitations, light interception is difficult to measure (Jung et al., 2018). Recently, many researchers have found light interception in plant canopy by 3D plant model and ray-tracing simulation with in terms of functional-structural plant model (Buck-Sorlin et al., 2011; Sievänen et al., 2014; Henke and Buck-Sorlin, 2018). This method can elucidate spatial light distribution on plant canopy as affected by light environment, furthermore, estimate photosynthetic rate based on light interception with photosynthesis model (Buck-Sorlin et al., 2011; Sarlikioti et al., 2011; de Visser et al., 2014; Kim et al., 2016; Jung et al., 2018). This *in-silico* analysis can reflect environmental factors affecting light interception such as planting density, facility structure, and features of light source, that compose the light environment of plant factories.

Recently, some studies applied 3D plant model and ray-tracing simulation to find the light interception of plant canopy under electrical lights in plant factories (Kang et al., 2016; Hitz et al., 2018). But the used plant models did not reflect actual plant structure with flat-shaped leaf model. In the interaction between light environment and plant canopy, however, plant morphology and structure are crucial factors deciding spatial canopy light interception (Burgess et al., 2015). Therefore, 3D plant model needs to precisely reflect the actual plant structure to assure the credibility of simulation result. In this respect, image-based 3D reconstruction can be a useful tool to construct elaborate 3D plant model (Burgess et al., 2017; Townsend et al., 2018). This method directly extracts plant structure from 2D or 3D images, which can be reconstructed to virtual 3D plant model with high accuracy. Therefore, by using the image-based 3D reconstruction method, elaborate 3D plant model can be constructed which induces precise analyzing of light interception.

The objectives of this study were to estimate light interception, photosynthetic rate, and light use efficiency of lettuces under LEDs by using 3D-scanned plant models and ray-tracing simulation, and to analyze the influence of light environment to canopy light interception under various scenarios.

LITERATURE REVIEW

Plant factory with electrical lights

The concept of using electrical light sources for crop cultivation in closed environment was beginning to emerge in 1980s (Davis, 1985; Hirama, 2015). Since then, because of full controllability of environment affecting plant and space-intensive production, plant factory with electrical light has been suggested as a solution for global climate issue and food production at expanding cities (Despommier, 2011; Kozai, 2013; Grammans et al., 2017). In the past, commercial light sources like fluorescent, metal halide, and high pressure sodium were used as electrical light sources for plant factory, but these light sources are developed for human-use and not optimum for plant lighting (Bula et al., 1991). In recent years, light emitting diode (LED) has been widely used for plant lighting with the advantages of selectable spectrum for high photosynthetic efficiency and small size which is suitable for multi-layer cultivation (Massa et al., 2008; Morrow, 2008). Moreover, high electrical efficiency compared with other light sources and decreasing production cost strengthen the usability of LEDs in plant factory (Pimputkar et al., 2009).

Lighting strategies in plant factories

To improve electricity use efficiency and productivity, several lighting strategies have been applied in plant factories. Some studies tried to reduce electrical energy consumption by changing irradiation area at different growth stage. Poulet et al. (2014) used targeted lighting system on lettuces and each LED was selectively switched considering canopy size. Also, Li et al. (2016) applied zoom lens system composed with LED-convex lens unit and Fresnel lens. These two studies resulted that electricity consumption was reduced compared with conventional full-coverage lighting. In these cases, plant yields were decreased, but high electricity use efficiencies were achieved considering electricity consumption and yield. Because light sources are generally positioned on plants in plant factories, light condition of beneath leaves are unfavorable. In this respect, Zhang et al. (2015) introduced supplemental LEDs under lettuces to resolve this problem and improve productivity. As a result, marketable ratio, total yield, and photosynthetic rate of outer leaves were significantly increased by upward lighting. However, the changes of light interception were not considered in these studies, which are directly affected by lighting strategy.

Ray-tracing simulation with 3D plant models

To examine the spatial light distribution on plant canopy, ray-tracing simulation was used with 3D plant models (Cieslak et al., 2008). This method was mainly applied on greenhouse environment and the effects of seasonal variation, canopy arrangement, and plant architecture on light interception were found under sunlight environment (Buck-Sorlin et al., 2011; Sarlikioti et al., 2011; de Visser et al., 2014; Kim et al., 2016; Jung et al., 2018). Especially, de Visser (2014) introduced supplemental LED modules and light use efficiencies with different lighting direction were analyzed. In these days, image-based 3D plant modeling was utilized to accurately reflect the structural effect of different genotypes on canopy light interception in cereal plants (Burgess et al., 2016; Townsend et al., 2018). In the case of plant factory, some studies applied simulation method to examine the changes of light interception under different light environment (Kang et al., 2016; Hitz et al., 2018). Recently, the reliability of ray-tracing simulation in an LED growth chamber was validated by comparing with actual measurement (Hitz et al., 2019).

MATERIALS & METHODS

Plant material

Lettuce (*Lactuca sativa* L., cv. Asia Heuk Romaine) seeds were sown in polyurethane cubes and seedlings were grown by deep flow technique (DFT) under fluorescence tubes with a photosynthetic photon flux density (PPFD) of 200 ± 10 μmol m^{-2} s^{-1}. After 3 weeks, the plants were transplanted to the DFT system with a planting distance of 20 cm. LED plates were used for light source with PPFD of 200 with an 8:2 ratio of red and blue LEDs. Yamazaki nutrient solution (Yamazaki, 1982) was used with electrical conductivities (ECs) of 0.6 ± 0.05 and 1.2 ± 0.05 ms cm^{-1} for two-week-old seedling and after transplanting, respectively. Temperature and photoperiod were set at 22℃ and 16/8 h (day/night), respectively. Nine lettuce plants were selected at 21 days after transplanting (DAT) and used for experiments.

Measurements in growth chamber

A closed growth chamber (100 × 80 × 50 cm) was used to measure the light intensity distribution and whole canopy photosynthetic rate (Fig. 1A). The ceiling of a growth chamber was constructed with transparent acryl for light penetration and the inner surface was covered with black board to normalize the reflected light. In addition, a plastic bed (76 × 48 × 10 cm) was positioned in the growth chamber for nutrient solutions and the composition of nutrient solution was the same as used in the DFT. Two LED plates (80 × 16 × 2 cm) were positioned on the growth chamber with an 8:2 ratio of red and blue LEDs. For precise simulation setting, datum point for light intensity was fixed in the central position of the bed. The plants were arranged at 3 × 3 isotropic form with two planting distances of 20 or 25 cm, which will be described as 20D and 25D hereafter in this paper, respectively.

Because light interception of plant canopy cannot be actually measured, light intensities at several points were used as indirect index to describe the accuracy of estimated canopy light interception. Light intensity was measured by a light meter (LI-250A, LI-COR, Lincoln, NE, USA) in the growth chamber with and without plants at fixed points (Appendix 1). In case of empty chamber, light intensities were measured at different heights. Due to the dense canopy structure of the lettuce plants, it is hard to measure the light intensity on different leaf layers or inner canopy. Therefore, when the plants were arranged, light intensities were measured between the plants only under the canopy. The PPFD in the growth chamber was set at 200 μmol m^{-2} s^{-1}.

Whole canopy photosynthetic rate was measured by a gas analyzer (LI-840A, LI-COR, Lincoln, NE, USA) connected to the growth chamber. To get the whole canopy photosynthetic rate, the growth chamber was enclosed and the change of CO_2 concentration was monitored at every second from 800 to 400 μmol mol^{-1}. And the difference in CO_2 concentration averaged for 3 min was used for calculation of whole canopy photosynthetic rate. To capture different photosynthetic rates at different light intensity, the PPFD was set at 100, 200, and 300 μmol m^{-2} s^{-1}. The set temperature was 22°C and the range of relative air humidity was 60 – 80% in the growth chamber. Air leakage from the growth chamber was measured at CO_2 concentration above 1000 μmol mol^{-1} and number of air exchanges was 0.0016 h^{-1}, which was used for estimating the photosynthetic rate.

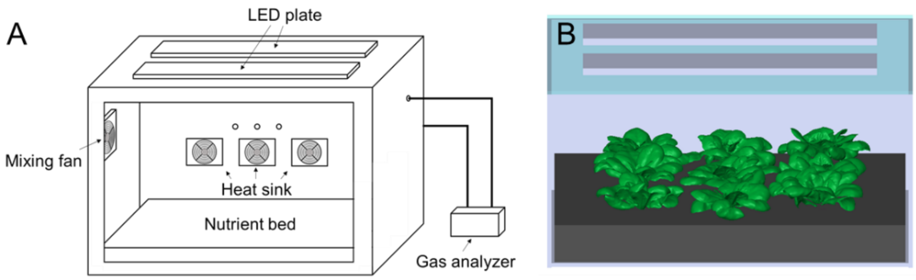

Fig. 1. A schematic diagram of a growth chamber with LED plates used for measuring light intensity and canopy photosynthetic rate of lettuce plants (A) and a virtual growth chamber reconstructed based on actual dimension (B).

Construction of 3D-scanned plant models

The lettuces plants used for measurements were scanned to reconstruct 3D-scanned plant models (3D-SPM, Fig. 3) with a high-resolution portable 3D-scanner (GO!SCAN50TM, CREAFORM, Lévis, Quebec, Canada). The resolution of scanner was set at 2 mm. Because inner and overlapped leaves are difficult to be recognized by 3D-scanner, each leaf was separately scanned. Total nine lettuces were scanned and leaves smaller than 2 cm were neglected. After scanning, scan data were incorporated to original plant structure based on positioning information using a scan software (Vxelement, CREAFORM, Lévis, Quebec, Canada). The holes and noises of 3D mesh data was fixed, and 3D mesh were reconstructed to surface model to perform ray-tracing simulation by a reverse engineering software (Geomagic Design X, 3D Systems, Rock Hill, SC, USA).

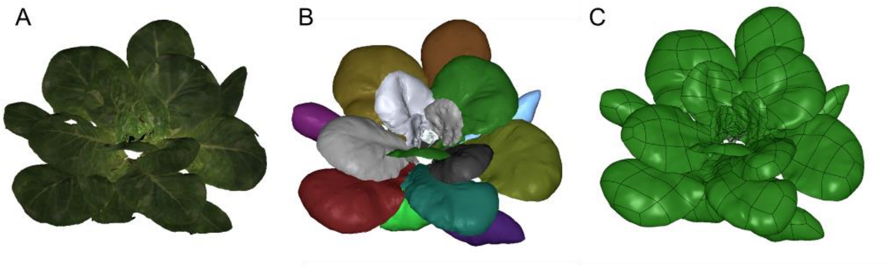

Fig. 2. Views of 3D-scanned data (A), 3D mesh (B), and reconstructed 3D-scanned plant model (3D-SPM, C) of a lettuce plant. 3D mesh was extracted from 3D-scanned data and converted to 3D-SPM usable for ray-tracing simulation.

Ray-tracing simulation

Because the path and energy of rays are changed by the optical properties of encountered object, transmittance and reflectance should be measured and reflected to virtual objects. To set the optical properties in ray-tracing simulation, transmittance and reflectance of leaf and black board were measured with a spectroradiometer (Appendix 2) (BLUE-Wave Spectrometer, StellarNet Inc., Tampa, FL, USA). Because leaf optical properties for different age or position showed no difference, average value for three points was used. Transmittance of black board was neglected, and ceiling of chamber was set as fully permeable material. Optical properties in range from 400 to 700 nm were applied on simulation considering spectrum range of used LED.

To perform ray-tracing simulation, virtual growth chamber and LED plate were reconstructed (Fig. 1B) based on measured dimension by a 3D computer-aided design software (Solidworks, Dassault Systèmes, Vélizy-Villacoublay, France). Total of 640 red LED chips and 96 blue LED chips were mounted on the LED plate considering dimensions and patterns. For each LED chip, spectral power distribution (SPD) and physical light distribution (PLD) were set as light source parameter. Spectrum distributions of red and blue LED were measured with spectroradiometer at 1 nm interval for SPD setting. For PLD, Lambertian distribution with half angle of 60° was set.

After virtual growth chamber setting, 3D-SPMs were disposed in virtual growth chamber to perform ray-tracing simulation (Fig. 1B). Because small interactive-spatial difference between plant and light model can induce different light interception, observed rotation angle and planting distances at actual plants were reflected to 3D-SPMs. To compare measured light intensity with simulation, virtual light sensor was placed at light measuring point.

The ray-tracing simulation was performed by using a ray-tracing software (OPTISWORKS, OPTIS Inc., La Farlède, France). Total emitted number of rays was set to 200 million which is suitable considering model size. To calibrate PPFD in virtual growth chamber, cylinder shaped detector was modeled based on quantum sensor dimension and position. By comparing LED power setting and absorbed PPFD of detector, LED outputs were set to 0.009, 0.018 and 0.027 W for red LED chips and 0.02175, 0.0435, and 0.06525 W for blue LED chips, representing PPFDs of 100, 200, and 300 μmol m^{-2} s^{-1}, respectively. In this case, emitted photosynthetic photon flux from whole LED chips were 79.3, 158.6, and 237.9 μmol s^{-1}, respectively.

Photosynthetic rate

Whole canopy photosynthetic rate was calculated by absorbed PPFD and photosynthesis model. For photosynthesis model, modified Faquhar, von Caemmerer, and Berry (FvCB) model by Qian et al. (2012) was used. To obtain

FvCB model parameters, photosynthetic rate was measured for upper and lower canopy by portable photosynthesis system (LI-6400, LI-COR, Lincoln, NE, USA) with 4 different CO_2 concentrations (100, 400, 800, and 1200 μmol mol^{-1}) and 8 different light intensities (0, 50, 100, 200, 400, 600, 900, and 1200 μmol m^{-2} s^{-1}). Leaf temperature was set to 22°C and relative humidity ranged from 60 to 70%.

Respiration rate was fixed at measured values of 0.75 and 0.41 μmol m^{-2} s^{-1} for upper and lower canopy, respectively. V_{cmax}, J_{max}, and CO_2 compensation point were obtained by non-linear regression for model parameters and were 68.324, 139.851, and 42.897 for upper layer and 46.423, 52.898, and 16.923 for lower layer. The efficiency of light energy conversion (α) and curvature value (θ) was fixed at empirical values of 0.18 μmol e^- μmol^{-1} and 0.7, respectively (Evans, 1989; Wullschleger, 1993).

Simulation result includes point cloud of 3D-SPM (x, y, and z coordinate) and absorbed light energy (W), which was converted to PPFD by conversion factor of 5.013 considering spectral distribution of LEDs used in this experiment. Through simulation result, photosynthetic rate on a single point (P_i, μmol m^{-2} s^{-1}) was calculated by following equation:

$$P_i = \min\{A_c(PPFD_i, Ci), A_j(PPFD_i, Ci)\} \qquad \text{Eq. 1}$$

where A_c and A_j are net photosynthetic rate (μmol m^{-2} s^{-1}) limited by rubisco activity and electron transfer rate, respectively. $PPFD_i$ is intercepted PPFD on single point (μmol m^{-2} s^{-1}) and Ci is intercellular CO_2 concentration (μmol mol^{-1}) calculated by Ball-Berry model based on external CO_2 concentration and relative humidity.

Whole canopy photosynthetic rate (P, μmol m^{-2} s^{-1}) was calculated by following equation:

$$P = \frac{\sum_{i=1}^{n}(P_i \times OA_i)}{LA} \qquad \text{Eq. 2}$$

where OA (m^{-2}) is occupied area of single point cloud. Because area of each point in simulation is differently described, every coordinate was rounded to 1 mm. n and LA means total point number and total leaf area (m^{-2}), respectively, and varied depending on each model size. To find the accuracy of estimated whole photosynthetic rate, whole photosynthetic rates were calculated for three different light intensities (100, 200, and 300 μmol m^{-2} s^{-1}), three different CO_2 concentrations (500, 600, and 700 μmol mol^{-1}) and two different planting distances (20D and 25D).

Light and energy use efficiencies were calculated with dividing estimated canopy photosynthetic rate by total emitted light energy from light source and electrical energy consumption. The total emitted light energies were 15.70, 31.39, and 47.09 W and electrical energy consumptions were 55.16, 116.36, and 184.5 W at PPFD of 100, 200, and 300 μmol m^{-2} s^{-1}, respectively.

Scenarios at different light environments.

Two scenarios were conducted to investigate the change of light interception under different light environments. In scenario 1, the change of canopy light interception by different lighting and planting distances was examined: four distances between light source and canopy top (25, 30, 35, and 40 cm) and three planting distance (15, 20, and 25cm; 15D, 20D and 25D hereafter) were set. The simulation for this scenario was performed in the growth chamber environment with 3 × 3 isotropic canopy, and the outputs were 0.018 and 0.435 W for red and blue LED chips, respectively.

In scenario 2, the change of light interception by different floor reflectance and planting distance was examined: three floor reflectance (0, 50 and 100%) and two planting distances (20D and 25D) were set. In this case, to consider only the effect of reflectance, surface light source whose light is uniformly distributed on plant canopy was used. The distance between surface light source and floor was 30 cm and PPFD was 200 μmol m^{-2} s^{-1} on the central position. Because light interception and reflective pattern is affected by adjacent canopy, adequate canopy arrangement should be determined. Therefore, I arranged 3D-SPMs to isotropic canopy from 1 × 1 to 7 × 7, and light interception of central model was observed. Next, the arrangement that showed stable decay of light interception at both 20D and 25D was used for scenario analysis.

Finally, another scenario was conducted to estimate the whole photosynthetic rate in a plant factory level. In scenario 3, I defined a virtual plant factory of five cultivation layers with 100 m^2 for each layer. Floor reflectance was assumed to be 50% and other simulation environment was identically set with the second scenario.

RESULTS

Validation of simulation results

To find the accuracy of ray-tracing simulation, measured light intensities in growth chambers with and without lettuces were compared with simulated ones. Without the plants, measured and simulated light intensities showed high linear relationship with R^2 and RMSE of 0.979 and 7.048 μmol m^{-2} s^{-1}, respectively (Fig. 3A). With the plants, the range of measured light intensities were overall lower than ones without the plants, in particular, near-zero light intensities were found at 20D. Linear relationship between measured and simulated light intensities was also found with the plants, but points are more spread from 1:1 line and error was larger with R^2 and RMSE of 0.864 and 21.598 μmol m^{-2} s^{-1}, respectively (Fig. 3B).

Estimated photosynthetic rates of canopy showed high linear relationship with measured ones with R^2 of 0.986 and RMSE of 0.16 μmol m^{-2} s^{-1} when PPFD, CO_2 concentration and planting distance were differently setup (Fig. 4).

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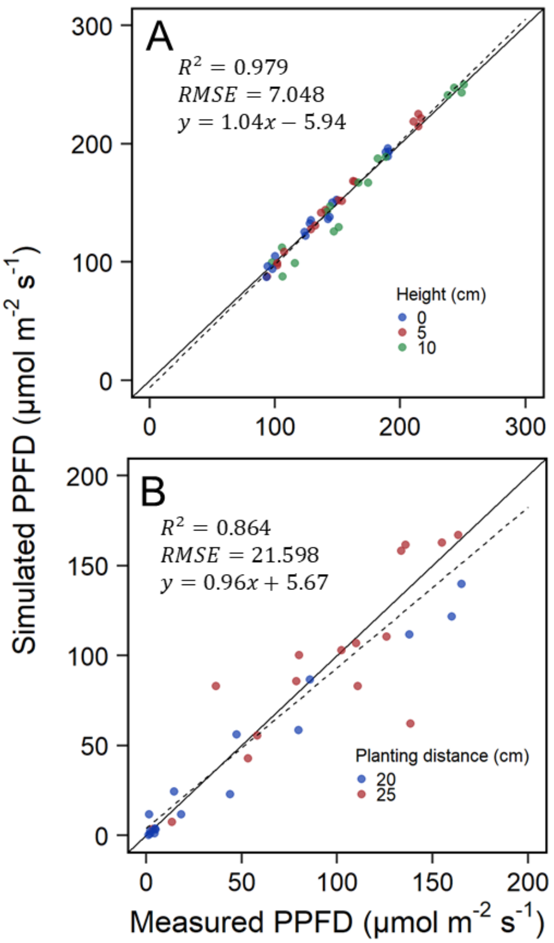

Fig. 3. Validation of the measured and simulated light intensities in the growth chamber without (A) and with (B) lettuce plants under LEDs. Light intensities were measured and simulated at heights of 0, 5, and 10 cm from the floor without lettuces (*n* = 48) and at height of 0 cm with lettuces at planting distances of 20 and 25 cm (*n* = 32).

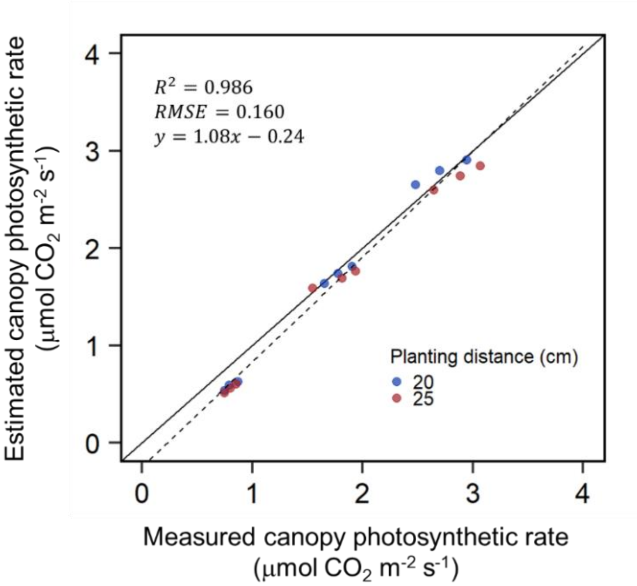

Fig. 4. Validation of the measured and estimated photosynthetic rates of the whole lettuce plants in the growth chamber at planting distances of 20 and 25 cm (n = 18).

Analysis of canopy light interception and photosynthesis

The simulation result shows that light interception and photosynthetic rate are heterogeneously distributed on plant canopy. Light interception of marginal lettuces was lower than central one, and the gap was larger at 25D (Fig. 5). When planting distance is changed from 20D to 25D, light interception of central lettuce was increased by 18.5%, but one of marginal lettuces was decreased by 5.5%. Distribution of photosynthetic rate showed similar pattern with light distribution (Fig. 6). Maximal photosynthetic rate was about 8 μmol CO_2 m^{-2} s^{-1} on the top of central lettuce, and on shaded canopy, where light interception was almost zero, photosynthetic rate was almost identical to respiration rate.

Light interception on each canopy layer was different at 20D and 25D (Table 1). Light interception on top layer was larger at 20D, but those on middle and bottom layer were larger at 25D. When ratio of intercepted PPF (PPF_I) to emitted PPF (PPF_E) from LEDs was analyzed on each canopy layer, about 21 – 23% of PPF_E was received by the top layer and only 3 – 4% was received by the bottom layer.

Whole canopy light interceptions were larger at 20D about 2.6% compared with 25D (Table 2). Because canopy light interception was almost proportionally increased by the change of LEDs output, light and electrical energy use efficiencies were determined by the changes in canopy photosynthetic rate and consumed electrical energy (Table 2). In this case, the efficiencies were not much different at PPFD of 200 and 300 μmol m^{-2} s^{-1}, but lower about 30% at PPFD of 100 μmol m^{-2} s^{-1}. Ratio of whole PPF_I on canopy to PPF_E, which represents the efficiency of lighting, was about 0.41 and 0.40 at 20D and 25D, respectively.

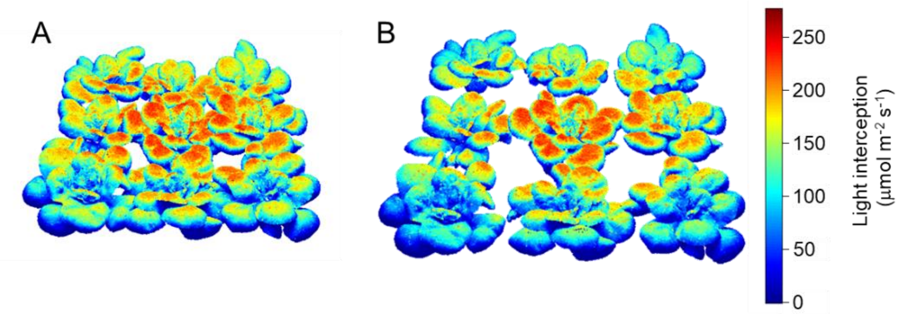

Fig. 5. Spatial distribution of light interception on 3D-scanned lettuce models in a growth chamber under LEDs at planting distances of 20 (A) and 25 (B) cm. Total emitted PPF was set to 158.6 μmol s^{-1}.

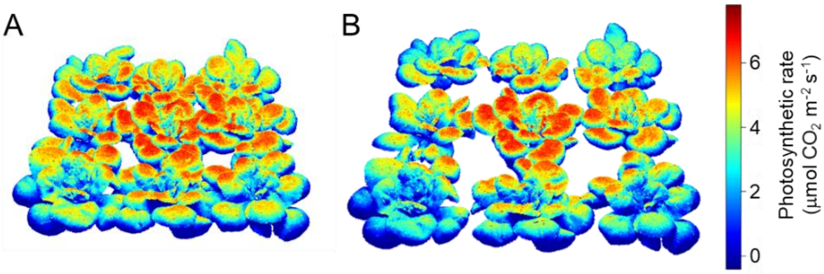

Fig. 6. Spatial distribution of estimated photosynthetic rates on 3D-scanned lettuce models in a growth chamber under LEDs at planting distances of 20 (A) and 25 (B) cm. Total emitted PPF was set to 158.6 μmol s^{-1}.

Table 1. Simulated light interceptions on different canopy layers of lettuce plants at planting distances of 20 and 25 cm. Total emitted PPF was set to 158.6 μmol s^{-1}.

Planting distance (cm)	Canopy layer[z]	Light interception (μmol m^{-2} s^{-1})	PPF_I[y] / PPF_E[x]
20	Top	124.0	0.237
	Middle	68.9	0.131
	Bottom	19.4	0.037
25	Top	111.1	0.213
	Middle	71.5	0.137
	Bottom	24.1	0.046

[z]Leaf area index of each layer was same.

[y]Means intercepted photosynthetic photon flux on each canopy layer.

[x]Means total emitted photosynthetic photon flux from light source.

Table 2. Canopy light interceptions, canopy photosynthetic rates, light use efficiencies, and electrical energy use efficiencies on of lettuce plants at planting distances of 20 and 25 cm. PPFD was set at 100, 200, and 300 μmol m^{-2} s^{-1}, and in this case, total emitted PPFs were 79.3, 158.6, and 237.9 μmol s^{-1}, respectively.

Planting distance (cm)	PPFD (μmol m^{-2} s^{-1})	Light interception (μmol m^{-2} s^{-1})	Canopy photosynthetic rate (μmol CO_2 m^{-2} s^{-1})	Light use efficiency[z] (g CO_2 MJ^{-1})	Energy use efficiency[y] (g CO_2 kWh^{-1})
20	100	35.4	0.59	1.51	1.55
	200	70.7	1.74	2.22	2.16
	300	106.1	2.79	2.38	2.19
25	100	34.5	0.56	1.44	1.48
	200	68.9	1.69	2.16	2.19
	300	103.4	2.74	2.33	2.14

[z]Canopy photosynthetic rate per emitted photosynthetic photon flux.

[y]Canopy photosynthetic rate per electrical energy consumption.

Scenarios at different light environments

Canopy light interception tended to decrease with increment of lighting distance, but in case of 20D and 25D, it was the highest at lighting distance of 30 cm (Fig. 7). At different planting distance, light interception at 20D and 25D resulted similarly, which was larger than that at 15D at the all lighting distances.

When canopy was arranged from 1 × 1 to 7 × 7, the light interception of central 3D-SPM was stabilized at 3 × 3 arrangement. So, 3 × 3 lettuce canopy was used for scenario of the floor reflectance (Fig. A3). Light interception was increased at both 20D and 25D with higher floor reflectance, but the effect was larger at 25D (Fig. 8). In this case, light interception of single lettuce was increased by 9.1% at 20D and by 25.8% at 25D when reflectance was changed from 0% to 100%. Additionally, increment of light interception at each canopy layer was almost similar.

In a whole plant factory level, 20D is expected to have higher productivity in assimilation about 9.3% (Table 3). In this case, the effect of planting number was larger than higher photosynthetic rate of each lettuce. By high floor reflectance, canopy light interception was more increased at 25D, but even at reflectance of 100%, light interception of 20D was larger. The CO_2 consuming rates of the plant factory were 401.1 and 366.7 g h^{-1} at 20D and 25D, respectively.

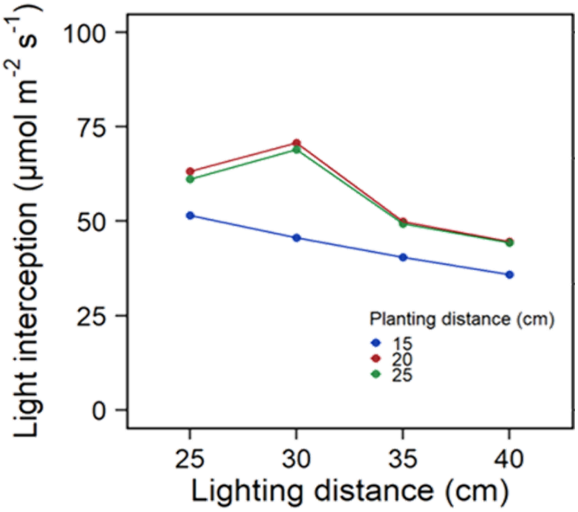

Fig. 7. Simulated light interceptions of lettuce canopy at a growth chamber conditions of three planting distances of 15, 20, and 25 cm; with four lighting distances of 25, 30, 35, and 40 cm.

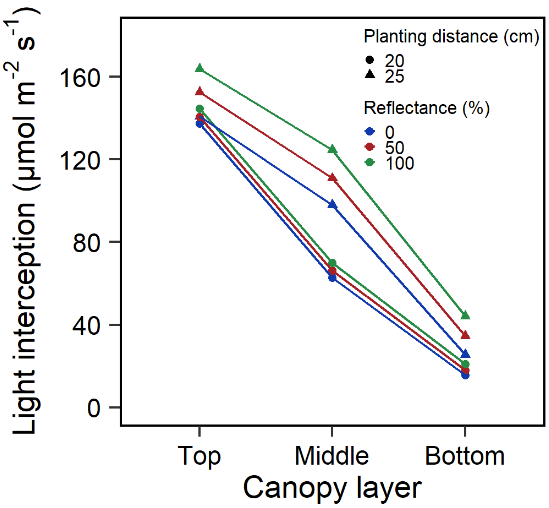

Fig. 8. Simulated light interceptions of lettuce canopy at three floor reflectance of 0%, 50%, and 100% with planting distances of 20 and 25 cm. Surface light was applied to exclude the influence of light source disposition.

Table 3. Photosynthetic rate of lettuce canopy in a plant factory with different planting distances of 20 and 25cm, and floor reflectance of 0, 50, and 100%. The plant factory was defined as containing five cultivation layers with 100 m^2 for each layer.

Planting distance (cm)	Floor reflectance (%)	Photosynthetic rate of single plant (μmol CO_2 s^{-1} / plant)	Number of plants per unit area (plants m^{-2})	Whole photosynthetic rate in the plant factory (μmol CO_2 s^{-1})	CO_2 consumption rate (g h^{-1})
20	0	0.19	25	2388.8	378.4
	50	0.20	25	2532.5	401.1
	100	0.21	25	2685.0	425.3
25	0	0.24	16	1994.4	315.39
	50	0.28	16	2315.2	366.7
	100	0.32	16	2633.6	417.2

DISCUSSION

3D-scanned plant model

In this study, the detailed plant morphology and structure of lettuces could be reflected on plant models by using 3D-SPM and affected the simulation results. When focused on detailed light distribution on leaves at 3D scene (Fig. 5), light intensity was decreased at marginal area of each leaf. Romaine lettuce, which was used in this study, has convex shape that outer part of leaf is almost perpendicular to light source. This morphological feature resulted that light was unevenly distributed on each leaf.

Simulation accuracy

The validation of light intensity showed that simulated and measured light intensities showed good agreements with high R^2 value without the plants, but with the plants, the R^2 was relatively low and RMSE was high (Fig. 3). This result could be also found in a previous research that conducted simulation using a growth chamber with electrical lights (Hitz et al., 2018; Hitz et al., 2019). In this case, the low R^2 of light intensities with plants does not actually mean that simulation is inaccurate, but rather can be attributed to some errors occurred in manual measurements. Because shaded and lighted parts were apparently separated within plant canopy under light sources, small change of sensor position or angle can induce large difference in measured value. On the other hand, virtual sensors can be precisely positioned based on input dimensions and fixed in simulation environment.

Canopy light interception under electrical lights

The quantitative light interception of plant canopy was investigated by using ray-tracing simulation and 3D-SPM. Moreover, by applying this method on different scenarios, the affection of various factors deciding light environment to canopy light interception. In general, light interception of plant is increased at low planting density due to reduction of mutual shading effect (Tanaka and Kawano, 1966; Goudriaan, 1995). However, in this study, the total light interception of was similar at different planting distances (Table 2), while light distribution on canopy was different (Fig 3.). This result can be explained by distinctive features of electrical light environment compared with sunlight, that light is not uniformly distributed on emitted area. At large planting distance, light interception of the central plant was increased by reduction of mutual shading effect, but, at the same time, light interception of the marginal plants distant from center of emitting area were decreased. Under electrical lights, light intensity is changed by the distance. Fig. 9 shows that overall light intensity was decreased at larger lighting distance, which induced the reduction of canopy light interception (Fig. 7). But, at the same time, light distribution is largely affected by the shape and placement of light source when lighting distance is close. And this resulted that canopy light interception was smaller at lighting distance of 25cm than that of 30cm at 20D and 25D. On the other hand, light interception of 15D was continuously increased when lighting distance became closer, which have small canopy concentrated on central area. When the reflectance of cultivation floor was increased, quantitative changes of light interception were similar on each canopy layer. Despite the increments were similar, this result indicate that high reflective material is effective for improving light interception of lower canopy because broadly using downward lighting is mainly emitted on upper canopy. As the increase rates of light interception at top and bottom layer were compared, they were almost similar at different PPFD. While increase rate of light interception at bottom canopy was about 72% and that at top canopy was about 16% when reflectance was changed from 0% to 100%.

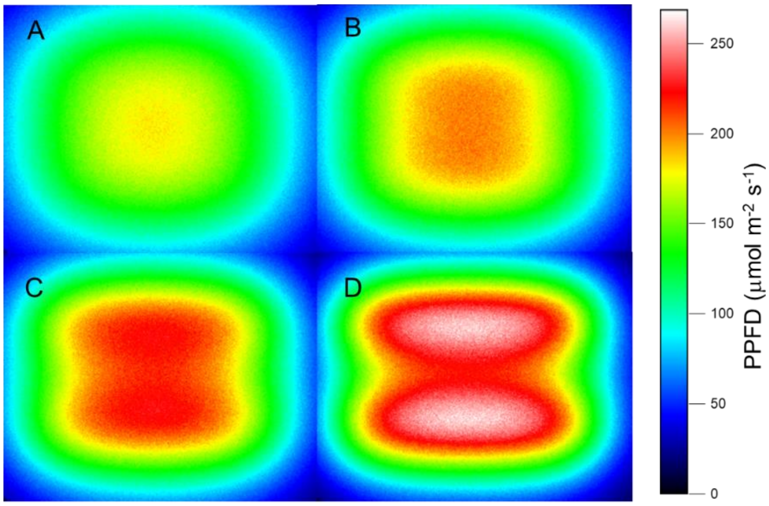

Fig. 9. Horizontal light distributions under LED plate at lighting distances of 25 (A), 30 (B), 35 (C) and 40 (D) cm. The detecting area is 96 × 76 cm and total emitted PPF was set to 158.6 μmol s^{-1}.

Canopy photosynthetic rate

The validation result of canopy photosynthetic rate under electrical lights showed high accuracy, but at low PPFD, estimated photosynthetic rates were lower than measured ones (Fig. 4, left 6 points). Photosynthetic rates were measured in PPFD-range of 0 to 1200 μmol m^{-2} s^{-1} when the parameters of photosynthesis models (e.g. V_{cmax}, J_{max}) were gained by regression, while canopy photosynthetic rates were measured below PPFD of 300 μmol m^{-2} s^{-1}. And the model parameters which can be applied for large PPFD range might underestimate the canopy photosynthetic rate at low PPFD.

The results show that distribution of photosynthetic rate was not much different compared with light distribution on plant canopy (Fig. 6, Fig. 7). This result is different from the previous researches in greenhouse under sun light or high-powered light source, where distribution of photosynthetic rate was more uniform than that of light interception on upper canopy (Jung et al., 2018). In this study, PPFD was set below than 300 μmol m^{-2} s^{-1} for both actual measurement and simulation. This PPFD range was relatively low considering light saturation point for photosynthesis, and photosynthetic rate was almost linearly increased with light intensity (Buck-Sorlin et al., 2011), which induced few differences between distribution of light interception and photosynthetic rate.

Perspectives

From the results, I confirmed that light interception of plant canopy under electrical lights is affected by several factors, like the placement of light sources and plants or the change of optical properties in surrounding environments. Therefore, under electrical lightings, canopy light interception and photosynthetic rate should be precisely quantified and estimated for efficient lighting. And the use of elaborate 3D plant model and optical simulation can be a good solution for designing plant factories. Under electrical light sources, light environment does not change by temporal or meteorological variable unlike outdoor or greenhouse cultivation. When light interception is estimated with simulation method, stable light environment increases the reliability. In developing light sources for plant lighting, the specifications of light source (e.g., PLD, SPD) can largely affect the canopy light interception and LUE. But interaction between plants in terms of canopy light interception is not usually considered. By analyzing the effect of light specifications to plant canopy with simulation, light sources can be designed and tested to find the actual lighting efficiency.

CONCLUSION

The canopy light interception was quantified by using light environment modelling, ray-tracing simulation and 3D-scanned plant models. Also, canopy photosynthetic rate could be estimated by simulation and FvCB photosynthetic rate model. Simulated light intensity and estimated photosynthetic rate showed high accuracy when compared with measured ones. When planting distance was increased, light interception of central plant was increased due to the reduction of mutual shading effect, but those of marginal plants were decreased due to heterogenetic light environments under electrical lighting. Through various scenarios, the changes in light interception at different light environments could be quantified. Also, the productivity and CO_2 consumption rate in whole plant factories could be estimated. This method could be useful for not only quantification of canopy light interception but also designing of electrical lighting systems for favorable light interception of plants in plant factories.

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ABSTRACT IN KOREAN

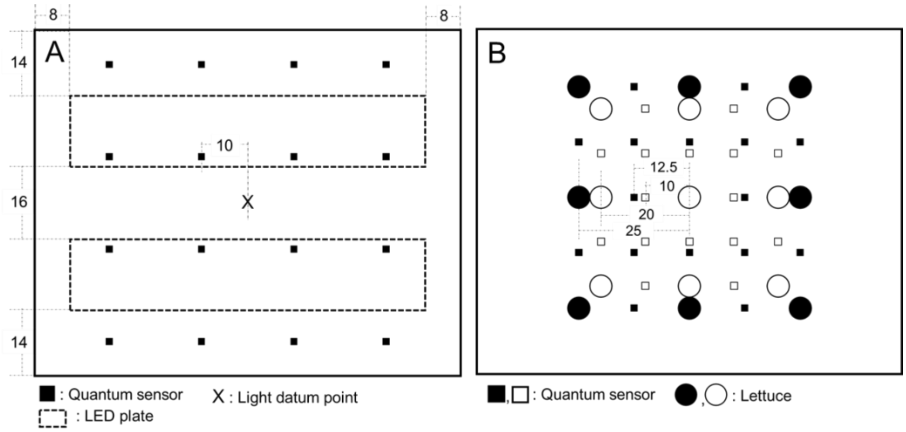
식물공장에서 전기 에너지 비용을 줄이기 위해서는 광 이용 효율을 높이는 것이 요구되며, 광 이용 효율을 평가하기 위해서는 다양한 인공광 조건에 대한 작물 수광의 예측이 필요하다. 본 연구의 목적은 시뮬레이션 방법을 통해 인공광 환경 하에서 작물의 수광과 광합성 속도 및 광 이용 효율을 예측하는 것이다. 작물의 수광량 예측을 위하여 3 차원 스캐너를 통해 구축된 식물 모델과 광 추적 시뮬레이션이 이용되었다. 작물 군락의 총 광합성은 수정된 Farquhar-von, Caemmerer-Berry (FvCB) 엽 광합성 모델과 시뮬레이션 결과를 바탕으로 추정되었다. 본 방법론의 정확성에 대한 검증은 실제 생장 챔버에서 측정된 광도와 광합성 속도를 시뮬레이션을 통해 얻어진 결과와 비교함으로써 이루어졌다. 또한 시나리오 분석을 통해 다양한 인공광 환경에서 작물 군락의 수광 변화를 분석하였다. 시뮬레이션을 통해 도출된 광도의 분포와 광합성 속도를 측정값과 비교한 결과 높은 정확성을 보이는 것이 확인되었다. 서로 다른 재식간격에서 군락 광 분포는 다르게 나타났지만 총 수광량은 유사하였다. 예측된 광합성 속도를 기반으로 광 이용 효율을 분석한 결과, 상추 군락의 재식 간격에

따른 광 이용 효율은 유사하였고 낮은 광도에서 약 30% 낮은 광 이용 효율을 보였다. 시나리오 분석 결과 광원과 군락 간의 거리가 멀어질수록 총 수광량은 점차적으로 감소하는 경향을 보였으나, 그 거리가 지나치게 가까울 경우 불균등한 광 분포로 인하여 오히려 수광량이 감소하였다. 재배상 표면에 높은 반사율을 적용하였을 경우에는 재식 간격이 클수록 총 수광량이 증가하였다. 본 연구에서 제시한 방법을 활용하여 식물공장의 광환경과 광합성 속도를 정량화하였고 광이용 효율을 추정할 수 있음이 확인되었다.

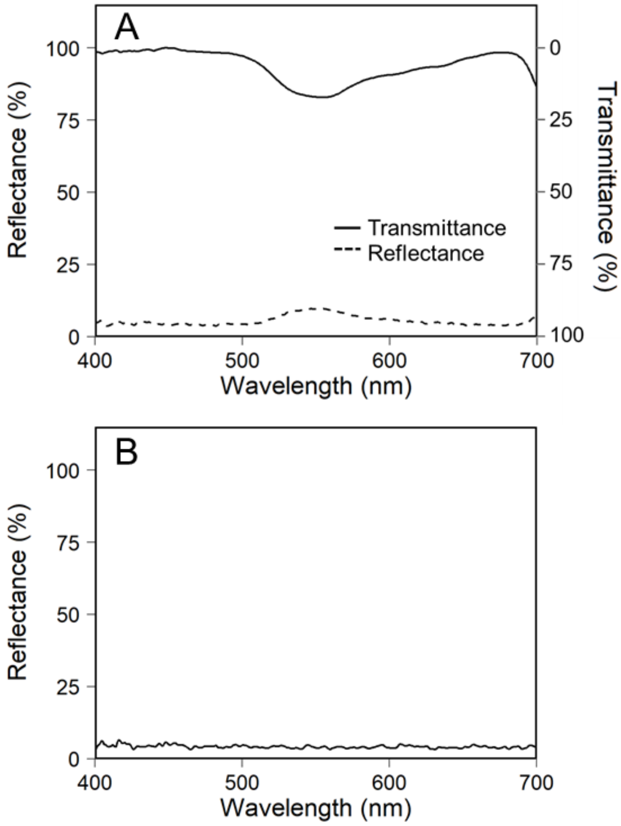
추가 주요어: 광 이용 효율, 광 추적 시뮬레이션, Farquhar-von, Caemmerer-Berry (FvCB) 엽 광합성 모델, 조명 거리, 반사율

학 번: 2017-22139

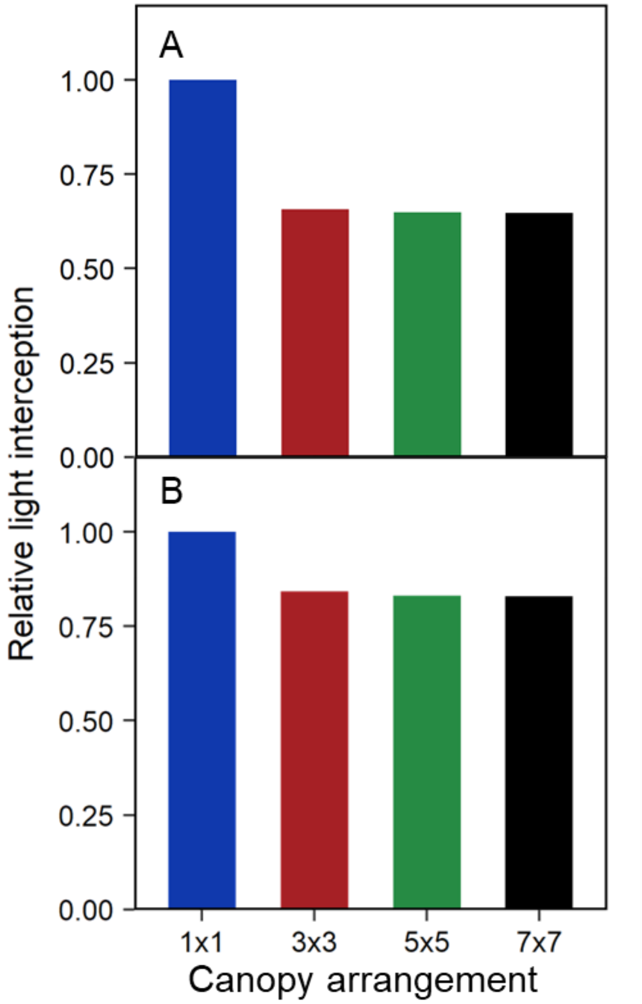
APPENDICES



Appendix 1. Positions of light intensity measurement using quantum sensor in the growth chamber without (A) and with (B) lettuce plants. In addition, the position of light datum point and LED plates (A) and the arrangement of plant canopy (B) are described.



Appendix 2. Measured transmittance and reflectance of lettuce leaf (A) and black board (B).



Appendix 3. Relative light interception of the central lettuce plant by isotropic canopy size at planting distances of 20 (A) and 25 (B) cm. The relative light interception was obtained based on the light interception at 1 x 1 canopy arrangement.