A THESIS FOR THE DEGREE OF MASTER OF SCIENE

Effects of Diffuse Glass on Light Distribution, Canopy Photosynthetic Rate, and Growth of Lettuce (*Lactuca sativa* L.) in a LED Plant Factory

LED 식물공장에서 산란유리가 광분포, 군락의 광합성 및 상추(Lactuca sativa L.)의 생육에 미치는 영향

BY

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ABSTRACT

LED is one of the most important light sources in plant factory. However, LED is not well penetrating into shaded volumes of plants grown in a small confined space due to the close distance to the plants and its small emission surface. The aims of this study were to determine the effect of diffuse glass on light distribution, canopy photosynthesis, growth of lettuce in a LED plant factory and to analyze the light absorption of the plants by 3D simulation. Horizontal and vertical light distributions were measured, and canopy photosynthetic rate was estimated by measuring the carbon dioxide consumption of the plants in sealed growth chambers. Diffuse glasses with haze factors of 80%, 40% and non-diffuse glass were set under the LEDs. The plants were grown at 150±15 μmol m^{-2} s^{-1} PPFD with 18/6 photoperiod, 1000 ppm CO_2 concentration, 22/18 ℃ (day/night), and 70% relative humidity. Light absorptions of 3-D lettuce models with vertical level were estimated by using 3-D simulation software. Under the diffuse glasses, horizontal light distribution was more uniform with deeper light penetration into the middle layer of the plants, and the growth indexes such as canopy photosynthetic rate, fresh and dry weights, and leaf area, LAI and SPAD-value were greater than the non-diffuse glass. The 3-D simulation results confirmed that diffuse glasses improved the light absorption efficiency in the top and the middle layers by reduction of the fluctuation of spatial radiation distribution, canopy distribution, and differences among in leaves.

Key worlds: Canopy photosynthesis rate, diffuse glass, light distribution lettuce. LED, plant factory

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INTRODUCTION

LED casts a directional light due to its small emission surface that causes shadow inside of plants (Bourget, 2008; Folta et al., 2005). Although LED is often installed close to the plant canopy, the light from LED is not well spread within close distance. It caused a limited penetration of light into dense crop canopy. These characteristics decrease the photosynthetic active radiation effectively used by plants and the growth of the plants. For preventing disadvantages of the LED, diffuse light is required to obtain more uniform light distribution within canopy.

Numbers of previous researches have focused on diffuse light in solar greenhouse. Young and smith (1983) reported that diffuse light was able to penetrate deeper into crop canopy. Compared to direct light, incidence of the diffuse light was scattered to all directions and generated more uniform distribution. Light fluctuation was smaller under diffuse glass compared to that under clear glass (Kempkes et al., 2012). A model, called INTKAM model, was developed to show that the diffuse light was able to penetrate deeper into the crop canopy (Elings et al., 2012). As a result, more light could be intercepted by the intermediate and lower leaf layers at vertical light irradiation in diffuse glass greenhouse (Li et al., 2012).

Under diffuse lights, photosynthesis could be enhanced compared with direct light at same light intensity. The diffuse light (fraction=0.7) enhanced the life-cycle canopy photosynthesis for hydroponic wheat (Cavazzoni et al., 2002). FV/FM was higher under diffuse light, resulting in less stress to plants (Li et al., 2012). RuBisCo content was found to be higher in diffuse light and contained more chlorophyll under diffuse glass greenhouse (Hemming et al., 2008b). Many researches showed that the growth and yield increased in diffuse glass greenhouse (Hemming et al., 2008b; Markvart et al., 2010; Victoria et al., 2012).

Most of the previous researches on diffuse light have been applied to solar greenhouses. However, these researches have significant implications on light distribution in LED plant factory because the optical similarity between solar radiation and light from LED, such as directionality of light and formation of hot-spots, may result in similar problematic light distribution, lowered light utilization efficiency, and decreased growth of plants. The objectives of this study were to determine the effect of diffuse glass on light distribution, canopy photosynthesis, and growth of lettuce in a LED plant factory and to analyze the light absorption of the plants by 3-D simulation.

LITERATURE REVIEW

Property of diffuse materials

Nowadays for obtaining diffuse lights, direct lights can be transformed into diffuse light with diffuse materials. Diffuse glasses, plastic films, and rigid plastics that can scatter the direction of incident light have been widely used in the illumination systems (Both, 2002). Adding some kinds of light scattering agents such as barium sulfate, silicon dioxide, polymethyl methacrylate into the polycarbonate or acrylic makes the direct lights scattering into the diffuse lights. The property of the polycarbonate with transmittance of 85% and the haze of 91% were used as LED diffuse material (Yang et al., 2011). To prevent the non-uniform distribution from center to edge, a sophisticated diffuser and lens system were introduced to mitigate the variation of light intensity (Morris et al., 2007) by increasing the edge of light intensity. However, this plastic category such as polycarbonate and acrylic and polyethylene usually has plastics age and when exposed under heat or the UV radiation, the white plastic would turn to yellow. The transmission of plastics would decrease with problem of aging and yellowing.

Nowadays diffuse glasses have been introduced into greenhouses. Diffuse glass was a mechanically stable and durable material (Hemming et al., 2008a) compared with the plastic because stability of glass is more than 30 years without aging and yellowing. The diffuse glass has a property of haze factor that was defined as a percentage of the transmitted light scattered with more than 2.5 degrees from the direction of the incident light (Fig.1A). The haze factor was highly dependent on the surface structure or the presence of certain pigments. The perpendicular transmittance indicated that the light transmission of incident light which perpendicular to the material surface. Hemispherical transmission was average transmission of rays at 0 °, 10 °, 20 °, 30 °, 40 °, 50 °, 60 °, 70 °, 80 °, and 90 ° under different angles of incidence.

Matt structure, prismatic structure, v-groove structure, textured and satin structure etc. were used in designing diffuse glasses. Those diverse special structures lead to scatter incoming lights (Fig. 1B.). Other types of diffuse glass scattered the light by adding scatter particles such as calcium phosphate during the manufacturing process (Espi et al., 2006). When the light hit the particle, it was refracted up and scattered in all directions (Fig. 1C.). Translucent opal glass was obtained by melting of the mixed batch materials, which have excellent optical properties of high heat resistance and high durability as a replacement for a polycarbonate diffuser (Ku et al., 2013).

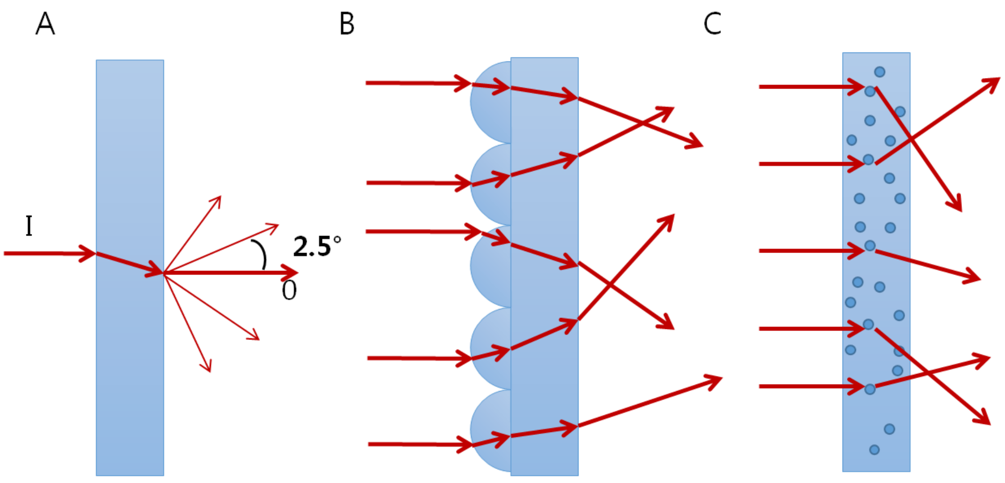

Fig.1. Definition of haze factor of diffuse glass. The haze factor is a percentage of the transmitted light scattered with more than 2.5 degrees from the direction of the incident light (A). Special surface structures leads incoming light scattered (B). Beams of light hitting the particle are refracted up and scattered (C).

Light and temperature distributions under diffuse glass

Shades inside greenhouses were generated due to structural components, facilities, crops, and clouds. Leaves were less shaded under diffuse glass than under direct light due to more uniform light distribution inside of canopy. Under the diffuse glasses, light fluctuation was smaller than under clear glass (Kempkes et al., 2012) and horizontal light distribution became more uniform (Hemming et al., 2008a). Particularly leaves in the middle layer of crop canopy intercepted more lights under diffuse glass (Li et al., 2012). The potential effect of diffuse glass in greenhouse depends on seasonal variation of solar radiation. As the ratio of direct radiation in summer is greater than that in winter, the effect of diffuse coverings gave more advantages in summer, resulting in an increased photosynthesis (Hemming et al., 2006). The Model, INTKAM showed that the diffuse light was able to penetrate deeper into the crop canopy (Elings et al., 2012). Average light intensity in the top layer was higher than that in the other layers due to the light interception. The experimental and simulation results showed more homogeneous distribution under diffuse light than direct light at a certain canopy depth.

High leaf temperature peaks occurred under clear glass greenhouse at noon that was higher than those under diffuse glass. The difference between leaf and air temperatures was 6 ℃, while remained below at 2 ℃ in the diffuse glass greenhouse. Leaf temperature and the difference between leaf and air temperatures decreased under diffuse glass (Dueck et al., 2012). At noon in summer, the radiation reached the threshold faster for closing the screen in the clear glass greenhouse than in the diffuse glass greenhouses. With and without shadowing screen, the transpirations were smaller under clear glass greenhouse compared to the diffuse glass greenhouse (Kempkes et al., 2012).

Plant growth under diffuse glass

The effect of diffuse light on canopy photosynthesis in plant growth chambers was analyzed by a layered canopy model. Compared with direct light at same light intensity, the diffuse light (fraction=0.7) enhanced the life-cycle canopy photosynthesis for hydroponic wheat by about 20% (Cavazzoni et al., 2002). These results indicated that ratio of diffuse lights can influence the experimental results conducted in controlled environments. Higher instantaneous crop photosynthesis was computed under fully-diffuse light and under fully-direct light in all layers (Elings et al., 2012). FV/FM was widely used as an index of plant stress because it rapidly shows the changes in the maximum quantum efficiency of PSII photochemistry. At noon, FV/FM was higher under diffuse glass greenhouse, indicating that the plants suffer less stress (Li et al., 2012).

Leaves in the middle layers of crop canopy as well as young leaves on the secondary branches had a higher rate of photosynthesis in diffuse glass greenhouse than clear glass greenhouse (Hemming et al., 2008b). Physiologically-older leaves situated deeper in the crop received less light, had less RuBisCo, and became photosynthetically less active. More chlorophyll contents and higher SPAD values was observed in upper and middle leaves (Hemming et al., 2008b). Diffuse light improved the productivity in greenhouse. Leaf area of chrysanthemums after 28 days under diffuse light treatment was 7% greater than the direct light. Total dry weight was 9% higher under diffuse light than that under direct light. 5.2% more stems and 6.1% more fresh weight were harvested in the diffuse glass greenhouse. Sweet pepper production can be potentially increased by 5-6% in summer by using diffuse coverings (Markvart et al., 2010; Victoria et al., 2012; Hemming et al., 2008b).

In addition, many recent researches showed that diffuse light improved the photosynthesis and productivity of crops from the small scale of growth chamber even to the large scale of ecosystem. Diffuse light deeply penetrated into crop canopy, making uniform light distribution with less shadow and hotspots, more light interception. Diffuse light led to more uniform climate in greenhouse and reduced fluctuation of spatial radiation distribution and reduced temperature hotspots at high irradiance, also resulting in less stress for plants.

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MATERIALS & METHODS

Growth conditions

Lettuce (*Lactuca sativa* L. Jeok Chuk Myeon) was grown in a plant factory located in Seoul National University. The plants were sown on sponges under fluorescent lamps at 150±15 μmol m^{-2} s^{-1} photosynthetic photon flux density (PPFD) with 16/8(day/night) photoperiod. Temperature was maintained at 22℃ and 18℃ during the day and at night, respectively. 14 days after sowing, Yamazaki's nutrient solution (EC 0.6 dS m^{-1}) was added. 21 days after sowing, the 16 plants were transplanted into each growth chamber with DFT system (deep flow technique). Two diffuse glasses (DA Glass, Poland) of haze factors of 80% and 40% (Haze 80% and Haze 40%), and without diffuse glass (control) were used (Table1 and Appendix 1). Warm-white LEDs were used as light sources. The plants were grown at 150±10 μmol m^{-2} s^{-1} PPFD with a photoperiod of 18h/6h (day/night). EC and pH were maintained at 1.2dS m^{-1} and 7.3-7.5, respectively. CO_2 concentration and relative humidity were controlled at 1000±50 ppm and 70%±5 with air velocity at 0.3m/s, respectively.

Measurements of light distribution and surface temperatures

The light intensity in the center of the bottom surface was fixed as 150 μmol m^{-2} s^{-1} PPFD. Light intensities at every 4cm of 17 rows and 17 columns were measured by a light sensor (LI-250A, LI-COR Biosciences, USA). Sigmaplot (Sigma 12.0, SigmaPlot™, USA) was used for drawing the contour plot and 3-D mesh plot. The light distributions among the control, Haze 40% and Haze 80% were compared. Surface temperatures of the glasses and walls were measured using an infrared camera (I5, FLIR Systems. USA). Leaf temperature was measured using the infrared camera at 0.5cm intervals of plant height.

Measurement of canopy photosynthetic rate and growth of the plants

Whole canopy photosynthetic rate was calculated by measuring whole-plant CO_2 consumptions in sealed acrylic chambers (Shin et al 2011). Environment conditions for the plant growth were the same as described before. The plants were transplanted into three closed acrylic chambers with diffuse glasses (Haze 80% and 40%) and without diffuse glass at 21 DAT. One hour after injecting $CO_{2,}$ until CO_2 concentration reached 1000 ppm and then turned off, CO_2 concentration was measured by a CO_2 Gas analyzer (LI-820, LI-COR, USA) connected to a data logger (CR-1000, Campbell Scientific USA). Leaf area was measured by a leaf area meter (Li-3100, LI-COR, USA) after the experiment finished. Canopy photosynthetic rate per leaf area was calculated by whole plant CO_2 consumptions and the leaf area was measured. The experiments were replicated three times. Growth indexes such as fresh weight, shoot fresh weight, root fresh weight, root dry weight, shoot and root ratios, leaf area, specific leaf area, and SPAD-value were measured.

3-D simulation for light absorption of the plants

For 3-D simulation, optical simulation software, Optisworks (OPTIS, France) performing ray-tracing was used. Totally 16 numbers of 3-D lettuces were mocked up as described in Fig.5. Values of reflectance, transmittance and absorptance of leaves measured by an integrating sphere (Lee, 2014) were used. LED was simulated as warm white 3000k with a view angle of 120 degrees. Glass transmittance, wall reflectance, and absorptance were set at 90%, 95%, and 5%, respectively. Light absorptions of the 3D lettuce model plants at heights of 0~6, 6~12, and 12~18cm were simulated and compared among the control, Haze 40%, and 80% under the light conditions of 10^8 rays per cm^2 and 1000 times of reflections. The Sum of the light absorption of leaf at each height, Σ (PPFD*leaf area), was calculated. In addition, the sum of the effective light absorption of leaf at each height, effective Σ (PPFD*leaf area), was calculated based on the light saturation point of lettuce (302 μmol m^{-2} s^{-1}) (Lee et al., 2012). Diffuse effects on light absorption of leaf were estimated by dividing effective Σ (PPFD*leaf area) by Σ (PPFD*leaf area) at each height.

Statistical analysis

Three haze factors of 0%, 40%, and 80% were designed in randomized complete block with three replications. The means were compared using Duncan's multiple range tests with significant difference at $p < 0.05$. Statistical analysis was conducted using the SAS (SAS Institute, USA)

Table 1. Haze factors, hemispherical and perpendicular light transmittances of the glasses used in the experiment.

Glass	Haze factor (%)	Perpendicular transmittance (%)	Hemispherical transmittance (%)
Control	0	100.0	100.0
Haze 40%	40	98.3	86.8
Haze 80%	80	97.9	77.9

RESULTS AND DISCCUSION

Horizontal light distribution and surface temperatures

Horizontal light distributions were more uniform in Haze 40% and 80% that in the control (Fig. 3). Numbers of peaks and troughs appeared in the control due to the near distance between LED and glass. In Haze 80%, the light distribution in the edge was more uniform than any other treatments. The surface temperatures of the LED panel ranged from 22.5 to 35.9 ℃ with lots of hotspots in the control (Table 2 and Appendix 2), while those of the diffuse glasses ranged from 22.2 to 24.2 ℃ and 22.1 to 24.2 ℃ in Haze 40% and Haze 80%, respectively, indicating that the diffuse glass absorbed and dispersed heat more uniformly into the ambient. The surface temperatures of wall ranged from 22.6 to 27.3 ℃ in the control, while ranged from 22.0 to 23.3 ℃ and 22.3 to 23.1 ℃ in Haze 40% and Haze 80%. Leaf temperatures increased with increasing of plant height (closer to light source) and fewer variations in temperature were observed under diffuse glasses (Fig. 4). Particularly, leaf temperatures showed no difference below 15cm and suddenly increased after that, however, there was no difference between Haze 40% and Haze 80%.

Lots of hotspots appeared under no diffuse glasses. Teng and Kuo (2010) reported that the hotspots became more obvious as the number of LED was greatly reduced. To prevent this problem, diffuse coverings was used to make light distribution more equally in greenhouses because light fluctuation was smaller under the diffuse glasses (Hemming et al., 2008a; Kempkes et al., 2012). Generally the light intensity influences the temperature distribution in confined space like plant factory. Diffuse glass absorbed the heat energy and dispersed heat into the environment and reduced the hotspots generated by LED panel, causing the temperature more uniformly. As the high temperature suppressed the growth and product quality of lettuce (Thompson et al., 2008), the control of temperature distribution in the plants was important. In this study, the temperature of lettuces at the top layer was over 30 ℃, but reduced around 25 ℃ by using the diffuse glasses. Dueck (2009) reported the similar results that the difference between leaf and air temperature remained below 2 ℃ by using the diffuse glass. In this study, diffuse glasses made more uniform distributions in horizontal light intensity and surface temperatures of glasses. Particularly leaf temperatures in the top layer became lower with fewer hotspots under the diffuse glasses.

Canopy photosynthetic rate and growth of the plants

The canopy photosynthesis rates became significantly higher with a higher haze factor, having 7.15, 7.31 and 7.71 μmol CO_2 m^{-2} s^{-1} in the control, haze 40%, and haze 80%, respectively (Fig. 5). The photosynthetic rate in haze 80% was higher by 7.8% than that in the control due to deeper penetration into the canopy under diffuse light. Total fresh weights, shoot and root fresh weights, shoot dry weight, leaf area, and SPAD value were significantly greater in Haze 80% than those in the control (Table 3). The fresh weight increased by 8.6% in Haze 80% compared to the control. Leaf area increased in the order of the control, Haze 40%, and Haze 80. There was no significant difference in TR ratio of shoot fresh weight between Haze 40% and Haze 80%. The plants grown without glass appeared smaller than those under diffuse glasses (Appendix 3).

The leaves at the middle and bottom layers under no diffuse glass received less light due to the interception and shading inside the canopy. By using diffuse glasses, the whole canopy photosynthetic and growth of the plants were improved in this study. Dueck et al. (2009) reported that higher photosynthesis was obtained with light absorption by the leaves at the middle layer of cucumber under diffuse light. The other reports also indicated that photosynthetic efficiency became greater with diffuse radiation (Gu et al., 2001). Hence increased diffuse radiation resulted in increased photosynthesis rate (Gu et al., 2003; Farquhar et al., 2003). For instance, the diffuse light resulted in a higher production of rose, varying from 9 to 10% at haze factors of 45 to 71 % (Dueck et al. 2009). More tomatoes were harvest under diffuse glass than under direct light (Dueck et al. 2012; Markvart et al., 2010). In this study, the more diffused LED light was penetrated deeper in the crop canopy led to higher photosynthetic rate and improved the growth of the lettuce.

Canopy light interception estimated by 3-D simulation

The experiments were replicated by three times. Light absorption ratios of the plants in the control, Haze 40%, and Haze 80% with plant heights of 0~6, 6~12, and 12~18cm were shown in Table 4. Average PPFD at the top layer of 12~18 cm was the highest in the control. Lots of hot spot appeared evenly among the leaves at the top layers, while light distribution was more uniform without hot-pots in haze 80%. Standard deviation of average PPFD in the control was larger than the diffuse glass especially at top layers. Light interception by leaves, Σ (PPFD*leaf area, PL), was greater in the control, particularly at the top layers. Effective PPFD was calculated and compared. Total effective light interception by leaves (effective PL, PLe) was changed to be greater in Haze 80% than in the control, particularly at the top layers. The values of PLe in the middle and bottom layers were not different among the treatments because measured PPFDs were equal to or lower than the light saturation point.

The leaves at the top layer occupied the 24.7% of the total leaf areas, but intercepted the 58.5% of the total light interception of the plants, indicating that the excess of light were concentrated on the top layer. The largest standard deviation of average PPFD at the top layer in the control indicated that non-uniform distribution with numbers of hotspots existed on the leaves at top layer due to the close distance between LED and plants. Considering that the light saturation and compensation points of lettuce are 302 and 18 μmol m^{-2} s^{-1} (Lee et al., 2012), after calculation of the effective Σ (PPFD*leaf area), PLe at the top layer increased by 7% and 12% in Haze 40% and haze 80%, respectively, indicating the diffuse glass uniformly distributed the light intensity at the top layer (Table 4). In the previous research, Young and Smith (1983) reported that diffuse light was able to penetrate deeper into crop canopy. Larger percentage of light were distributed and scattered in the middle layer of plants. INTKAM Model suggested that the diffuse light penetrated deeper into the crop canopy (Elings et al., 2012). Experimental results also showed that production potentially increased by 5-6% in summer by using diffuse coverings (Markvart et al., 2010; Victoria et al., 2012; Hemming et al., 2008b). Most of the researches were conducted in the greenhouses cultivating fruit vegetables or flowers having long stems and showed the clear effect of diffuse light on better light penetration into the crop canopy resulting in better growth. However, in LED plant factory, the effect was mainly from the reduction of hotspots at the top layer and improvement of effective light absorption rather than light penetration into the middle layer. This effect might be changed depending on the plant shape and the distance, particularly the portion of the leaf areas at the top layer. The greater the portion was higher, the more the effect of the diffuse light on the effective light absorption of the leaves at the top layer.

In this study, more uniform light distribution with less hotspots was obtained under diffuse glasses in the LED plant factory. Canopy photosynthetic rate was higher and the growth of the plants was better under diffuse light due to more uniform light distribution vertically and horizontally in the plant factory. The estimated the light absorption of leaves by 3-D simulation showed the same trends as those experimentally observed. It is concluded that the diffuse light will improve the productivity of plants with better uniform distributions in light intensity and temperature in LED plant factory.

Table 2. Surface temperatures of glasses (or LED panel) and walls under no diffuse glass, diffuse glasses with haze factors of 40% and 80%.

Surface temperature (℃)	Haze factor		
	Control	40%	80%
LED panel or glass	22.5~35.9[z]	22.2~24.4	22.1~24.2
Wall	22.6~27.3	22.0~23.3	22.3~23.1

[z]Surface temperature of the LED panel without diffuse glass.

Table 3. Growth indexes under no diffuse glass (control), diffuse glasses with haze factors of 40% and 80%.

Growth index	Haze factor		
	Control	40%	80%
Total FW[z] (g)	81.51b[y]	85.18ab	88.54a
Shoot FW (g)	69.59b	72.49ab	75.48a
Shoot DW (g)	3.91b	4.17ab	4.42a
Root FW (g)	11.91b	12.69ab	13.06a
Root DW (g)	0.71a	0.72a	0.73a
TR ratio (FW)	9.87a	8.99b	8.75b
Leaf area (cm^2)	1065.60c	1138.35b	1267.01a
SPAD value	31.60b	33.78ab	36.02a

[z]Same letters in the raw were not significantly different at *p<0.05*.

Duncan's multiple range test (DMRT).

[y]FW and DW mean fresh weight and dry weight, respectively.

Table.4. Vertical light distribution and plant light absorption under no diffuse glass (control), diffuse glasses with haze factors of 40% (Haze 40%) and 80% (Haze 80%) at heights of 0~6, 6~12, and 12~18cm.

Haze factor	Height (cm)	PPFD[z] ($\mu mol\ m^{-2}\ s^{-1}$)	Σ Leaf area (m^2, LA)	Σ(PPFD*LA) (PL)	Vertical ratio of PL	Effective PL (PLe)
Control	12~18	311.80±148.24[z]	0.41	127.84	0.59	98.06
	6~12	100.84±10.14	0.85	85.71	0.39	85.71
	0~6	12.15±0.41	0.40	4.86	0.02	4.86
	Total		1.66	218.40	1.00	188.63
Haze 40%	12~18	286.78±73.77	0.41	117.58	0.58	106.76
	6~12	94.86±7.45	0.85	80.63	0.40	80.63
	0~6	12.13±0.37	0.40	4.85	0.02	4.85
	Total		1.66	203.05	1.00	192.24
Haze 80%	12~18	280.46±43.73	0.41	114.99	0.58	109.36
	6~12	93.27±5.38	0.85	79.28	0.40	79.28
	0~6	12.08±0.32	0.40	4.83	0.02	4.83
	Total		1.66	199.10	1.00	193.47

[z]Photosynthetic photon flux density ($\mu mol\ m^{-2}\ s^{-1}$) at each layer.
[y]Means±SD (n=192, 12 leaves x 16 plants at each layer).

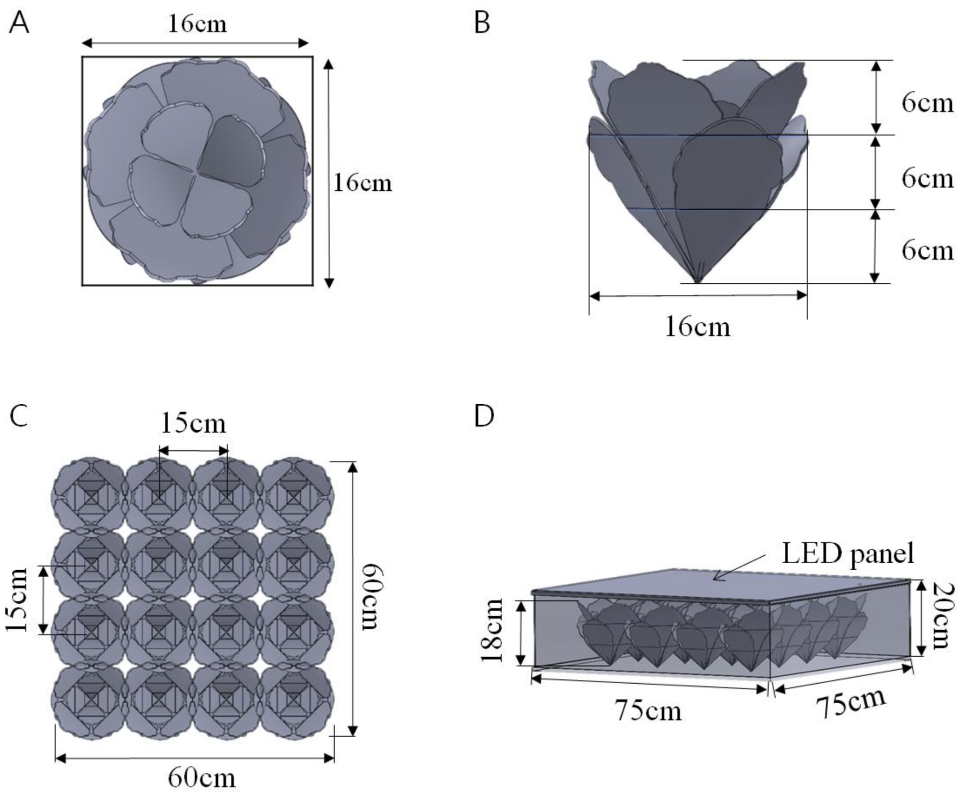

Fig. 2. Mockups of 3-D lettuce at 21 DAT: top view (A), side view (B), top view of 16 plants (C), and the plant growth module (D).

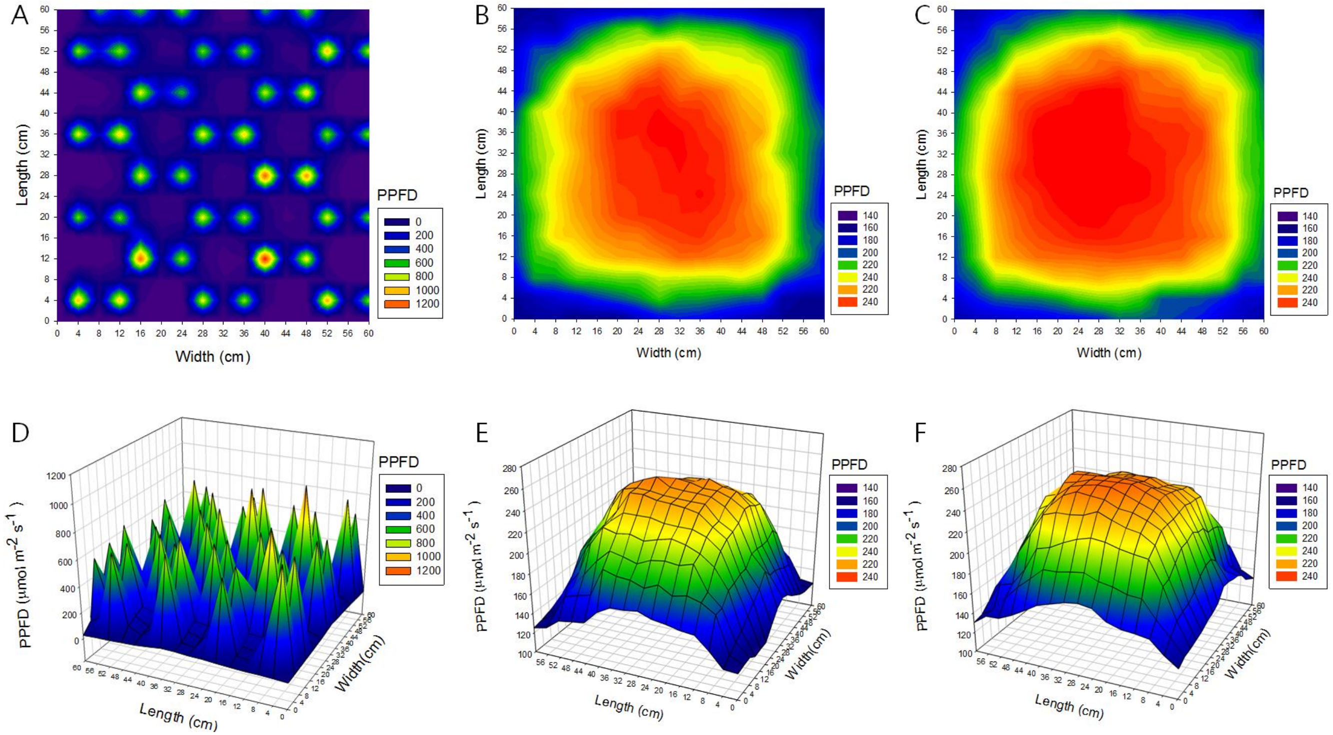

Fig.3. Horizontal light distributions under no diffuse glass (control, A and D), diffuse glass of haze factors of 40% (B and E), and 80% (C and F), respectively.

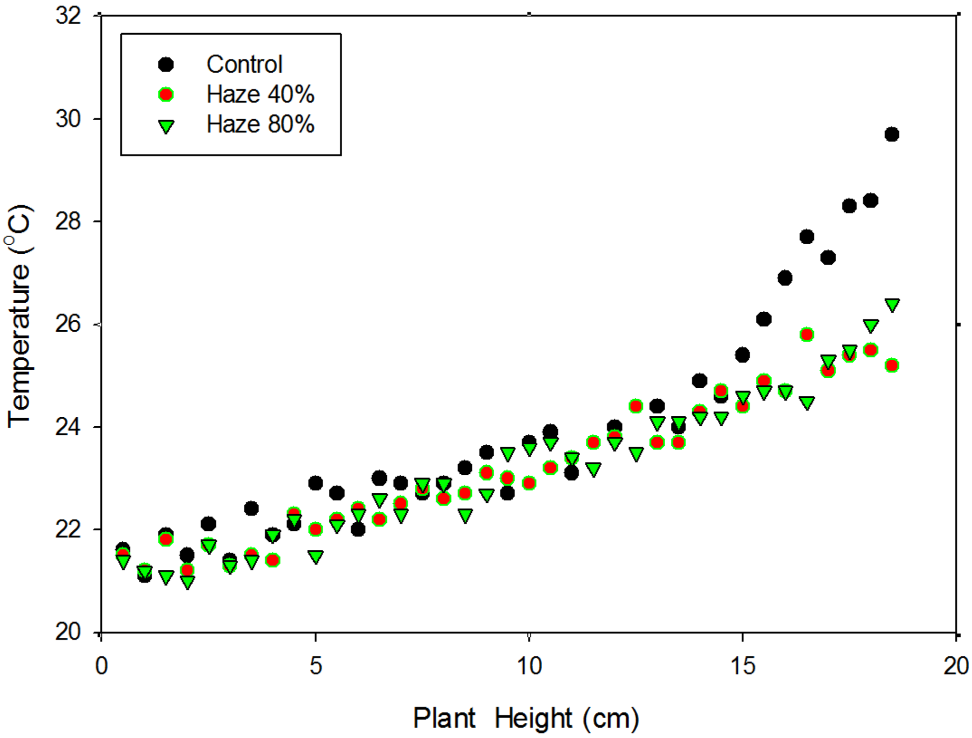

Fig.4. Leaf temperatures of lettuces with plant height under no diffuse glass (control), diffuse glasses with haze factors of 40% (Haze 40%) and 80% (Haze 80%).

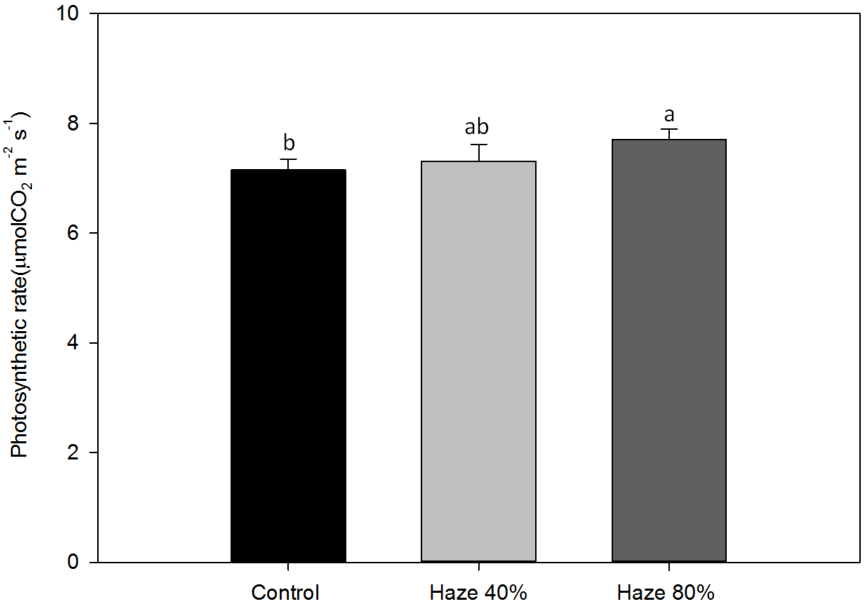

Fig. 5. Canopy photosynthetic rates of lettuces under no diffuse glass (control), diffuse glasses with haze factors of 40% (Haze 40%) and 80% (Haze 80%). Same letters in the bars were not significantly different at $p<0.05$. Duncan's multiple range test (DMRT).

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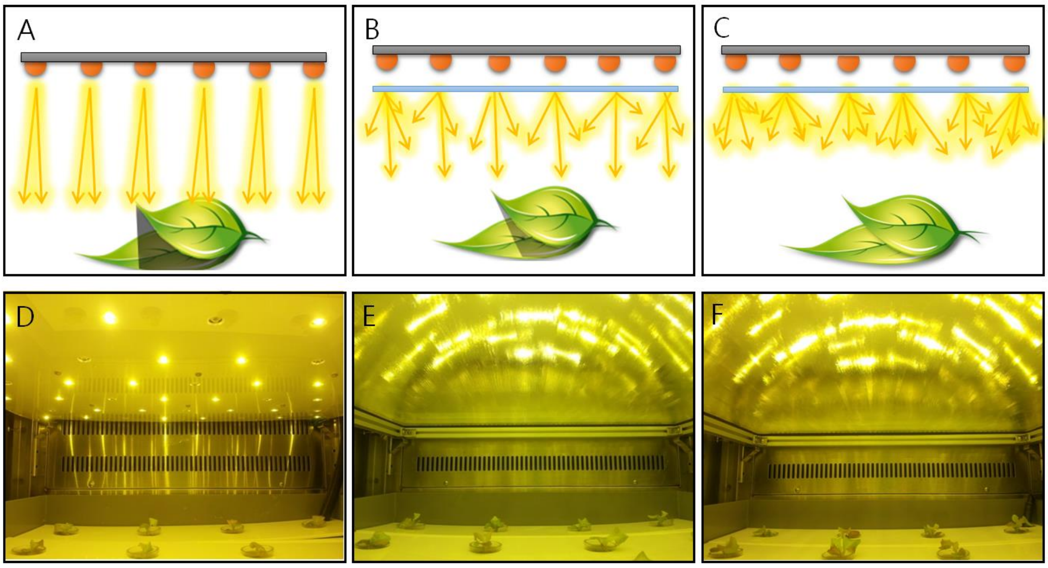
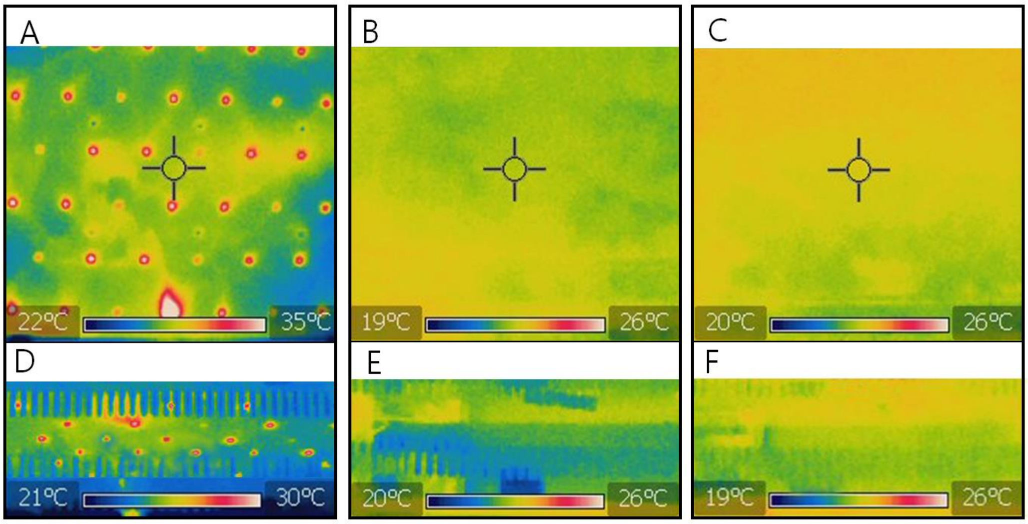
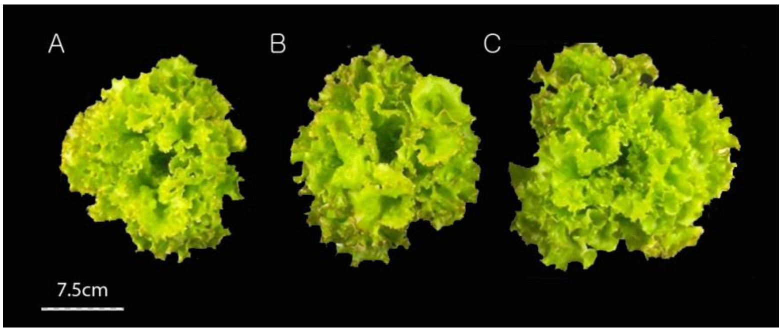
APPENDIX



Appendix 1. Concept of light direction under non-diffuse glass (control, A), diffuse glasses with haze 40% (B) and 80% (C). Light environments inside the growth chambers under the control (D), diffuse glasses with haze 40% (E) and 80% (F).



Appendix 2. Surface temperatures of the glasses and walls under non-diffuse glass (control, A and D), diffuse glasses with haze 40% (B and E) and 80% (C and F), respectively.



Appendix 3. Growth of lettuce plants under non-diffuse glass (control, A), diffuse glasses with haze 40% (B) and 80% (C).

ABSTRACT IN KOREAN

LED는 식물공장에서 중요한 인공광원 중의 하나이다. LED는 발광 면적이 적고, 작물과의 거리가 근접하여 설치되기 때문에, 좁은 공간에서 재배되는 작물 내부까지 광의 영향이 미치기 힘들다. 본 논문은 LED 식물공장에서 산란유리의 사용이 광분포, 수광량, 광합성 및 작물 생육에 미치는 효과를 실험적으로 분석하고, 작물의 수광량을 3-D 시뮬레이션으로 분석하는 것을 목적으로 하였다. 산란광 처리로 산란율(Haze factor) 40% 및 80%의 산란유리를 사용하였으며 대조구로는 유리를 사용하지 않았다. 수평, 수직 광분포를 측정하였고, 생육 챔버에서 이산화탄소 흡수량을 측정하여 광합성을 추정하였으며, 상추(*Lactuca sativa* L.)의 생육을 조사하였다. 백색 LED 150μmol m^{-2} s^{-1}의 광조건에 낮과 밤의 광주기는 18h/6h로 설정하였다. 이산화탄소 농도는 1000ppm, 온도는 낮과 밤은 22/18 ℃, 상대 습도는 70%, 풍속는 약 0.3 m/s로 설정하였다. 밀폐 챔버를 사용하여 동일한 환경조건에서 광합성속도를 측정하였다. 또한 3-D 광분석을 통하여 작물의 높이에 따른 광수광량을 추정하였다. 산란광을 사용하였을 경우, 수평 광분포가 보다 균일하였으며 내부 온도 및 엽온도의 변동이 줄었다. 결과적으로

상추의 생육을 증진시키면서 군락 광합성, 생체중, 건물중, LAI, SPAD 값이 높아졌다. 3-D 시뮬레이션을 통하여 산란광의 적용을 통하여 공간적 광분포 차이, 군락 내 광분포 차이, 엽 간의 광분포 차이 등을 감소시켰고 작물 중간층 엽의 수광율을 증가시키는 것을 확인하였다.

주요어: 군락 광합성, 광분포, 산란유리, 3D 시뮬레이션, LED 식물공장