Effect of Distribution of Photosynthetic Photon Flux Density Created by LEDs and Condenser Lenses on Growth of Leaf Lettuce (*Lactuca sativa* var. *angustana*)

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Plant factories have been receiving attention recently as a new vegetable production system. However, the high cost of producing vegetables in plant factories is a problem. An effective irradiation method was investigated to reduce the use of electric energy for light. A combination of LEDs and condenser lenses was constructed with the goal of having most of the light absorbed by a plant. Fresh weight, stem length, and number of leaves of leaf lettuce were measured under 12 different distributions of photosynthetic photon flux density (PPFD) created by the combination of three types of condenser lenses with the Full Width Half Maximum (FWHM) angles of 7°, 13°, and 35° and four LED driving currents of 0.2, 0.3, 0.4, and 0.5 amperes (A). Growth of lettuce was influenced by the distribution of PPFD using the same electric current. The choice of lens increased the fresh weight by 18% under the relatively strong light intensities of 0.4 A and 0.5 A. The combination of an electric current of 0.4 A with a lens of FWHM angle 13° produced the most efficient growth from a growth efficiency point of view.

Keywords : energy saving, growth efficiency, lens, lettuce, light flux distribution

INTRODUCTION

Plant factories have attracted attention as a new type of plant production system. Artificial light plant factories offer high efficiency of land use because they can produce vegetables in a multilayered system, allowing them to be built in a metropolis region where land is expensive (Ikeda et al., 1992). This characteristic offers the advantage of being in a high consumption area and having potentially lower transportation costs of vegetables. However, the production cost in artificial light type plant factories is still high, and this cost has deterred the spread of the plant factory system (Watanabe, 2011). Because the production cost of vegetables cultivated in a plant factory naturally varies according to the scale of facilities, the type of equipment, and so on, it is not easy to quantify costs. However, generally, the initial set-up cost, operating cost, and cost of personnel are a large proportion of the total production costs. The operating cost includes the electricity bill for lighting to allow the plants to photosynthesize and for air conditioning to control the temperature inside the plant factory. In the case of an artificial type plant factory, the lighting generates heat, and the air conditioning is necessary to remove this heat. Therefore, if the power consumption for lighting can be reduced by making the lighting system more efficient, the electric power required for air conditioning may also be reduced.

Current commercial operations typically apply uniform light to cultivation beds. One week after the seeds are

planted, lettuce seedlings are usually transplanted to a cultivation bed. The growth of lettuce in the first 2 weeks after transplant is still slow and each seedling occupies only a small space in a cultivation bed. Most of the light that falls on the cultivation beds is not absorbed by plants and is wasted.

Because the light environment is one of the most important factors in plant growth, there has been extensive research on the relationship between light and plant growth. Monteith (1965) reviewed models of light distribution in field crops. Research using LED for plant growth has been reported since 1990s. Bula et al. (1991) added a red LED array to blue fluorescent lamps to conduct the experiments with leaf lettuce, and reported that electrical energy conversion efficiency was greatly improved using the LEDs. At that time, a blue LED was under development stage and had not sufficient light intensity. Therefore studies using red LEDs have been performed. Hoenecke et al. (1992) also used the combination of red LEDs and blue fluorescent lamps to estimation of importance of blue light for plant growth. LEDs began to be investigated for tissue culture system (Miyashita et al., 1995). However, since the price of LEDs was still high in the 1990s, LEDs were used only for basic research rather than commercial use. In recent years, LEDs have become more common and the prices of LEDs have fallen, allowing them to be applied in the agricultural field. Use of LEDs in agriculture has become realistic, and applied research of LEDs as supplemental lighting for tomato (Lu et al., 2012), light source for germination and growth of seedlings (Godo et al., 2011),

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extended light (Ohashi-Kaneko et al., 2010) have been reported.

However, there is little research on efficient irradiation of plants using LEDs. The objective of this project was to find an effective irradiation method that would ensure that most of the light provided by an LED and lens system is absorbed by a plant. We demonstrated that we were able to reduce electric energy use per unit of fresh weight of lettuce produced, relative to the amount used in a currently operating commercial plant factory. Currently we are trying to manufacture a prototype lighting apparatus modified a commercially available light source based on this finding.

MATERIALS AND METHODS

The species used in this project was leaf lettuce (*Lactuca sativa* var. *angustana*). Leaf lettuce seeds were sown in urethane media soaked in sufficient water in a plastic tray (360 mm × 270 mm × 65 mm). The tray was placed in a growth chamber where air temperature was maintained at 23°C during the day and 18°C during the night. Fluorescent lamps (Monocute HF, MonoQtex Co., Ltd.) provided photosynthetic photon flux density (PPFD) of 100–150 $\mu\text{mol m}^{-2} \text{s}^{-1}$ on the urethane level with a 14-hour photoperiod for 7 days. The seedlings were then transplanted to a cultivation bed. A small hydroponics system was manufactured for this experiment (Fig. 1). A cultivation bed made of styrofoam (Width (W) 210 mm × Depth (D) 300 mm) was floated in a plastic tray (W 220 mm × D 310 mm × Height 50 mm) containing 3 liters of nutrient solution. The nutrient solution, which was completely replaced twice a week, was “Otsuka A” (Otsuka Chemical Co., Ltd.) adjusted to EC 1.95 dS m^{-1} and pH 6.2.

LED light source

Three white LEDs (Luxeon Rebel Star LXMS-PWC1-0070TRAY — white, Color temperature: 6,500 K) attached to a LED lens holder with a heat sink (Advanced Thermal Solutions, Inc. ATS-54210W-C2-R0) were manufactured by way of trail (Fig. 2). Three different lenses with the Full Width Half Maximum (FWHM) angles of 7°, 13°, and 35° (FWHM: 7°[Part No: 10193], 13°[10208], 35°[10196];

Carclo Precision Optics Co., Ltd.) were chosen and we named them “narrow lens,” “medium lens,” and “wide lens,” respectively. We prepared four sets of LEDs each containing three lenses of the same type (Fig. 2) to create a total of twelve sets.

Experimental procedure

Twelve sets of LED light systems (four sets for each type of lens) were connected in series and a power supply unit (EX-375US, TAKASAGO, Ltd.) provided a constant current. The amount of electricity provided is shown in Table 1. We conducted four experiments to vary the light intensity by changing the LED driving current by 0.1 ampere (A), starting at 0.2 A and going up to 0.5 A. The PPFD distributions on the cultivation bed using the three types of lenses at 0.5 A are shown in Fig. 3. Distribution of PPFD varies widely depending on the type of lens. However, the brightest spot was directly beneath the center of light apparatus in all types of lens. The maximum and average PPFD values under 0.5 A were 855 and 199 $\mu\text{mol m}^{-2} \text{s}^{-1}$ under the narrow lens, 422 and 170 $\mu\text{mol m}^{-2} \text{s}^{-1}$ under the medium lens, and 174 and 95 $\mu\text{mol m}^{-2} \text{s}^{-1}$ under the wide lens, respectively. The maximum and average PPFD values in all experimental conditions are shown in Table 2.

Our experiment was designed to examine the influence of the PPFD value on plant growth by measuring the amount of light condensing to a plant. The 12 cultivation devices were installed in a container-type plant factory where temperature and humidity were regulated. The different experimental conditions are shown in Table 3. The experimental period lasted for 5 weeks after transplant, and the results were obtained by harvesting the plants and measuring their fresh weight, number of leaves, stem length, and dry weight.

RESULTS AND DISCUSSION

Fresh weight

The effect of light flux distribution provided by the different types of lenses on fresh weight of harvested plants for each driving current is shown in Fig. 4.

At 0.2 A, the fresh weight of the harvested lettuce did

Fig. 1 Experimental setup showing cultivation bed and LED light source.

Fig. 2 Prototype LED light source.

Table 1 Electric power and daily electric energy.

Setting LED forward current (A)	0.2	0.3	0.4	0.5
Electric voltage (V)	2.87	2.94	2.99	3.03
Electric power (W) per LED	0.57	0.88	1.20	1.52
Daily electric energy (Wh) per unit experimental setup	24.1	37.0	50.2	63.6

Photoperiod=14h

Table 2 Maximum and average PPFD values under all experimental conditions.

LED forward current (A)	Maximum PPFD ($\mu\text{mol m}^{-2} \text{s}^{-1}$)		
	narrow lens	medium lens	wide lens
0.2	376	182	98
0.3	548	251	120
0.4	663	322	149
0.5	855	422	174

LED forward current (A)	Average PPFD ($\mu\text{mol m}^{-2} \text{s}^{-1}$)		
	narrow lens	medium lens	wide lens
0.2	92	81	46
0.3	129	111	64
0.4	162	141	77
0.5	199	170	95

Fig. 3 Photosynthetic photon flux distribution on the cultivation bed using three types of lenses. LED forward current was set at 0.5 A.**Table 3** Environment conditions during the experiment.

germination to transplant	DT/NT ($^{\circ}\text{C}$)	23/18
	PP (hr)	14
transplant to harvest	DT/NT ($^{\circ}\text{C}$)	23/18
	PP (hr)	14
	EC (dS m^{-1})	1.95
	pH	6.2

DT: day temperature, NT: night temperature, PP: photoperiod

not reach 50 g under all types of lenses, and it is clear that light intensity in this driving current was not sufficient to grow lettuce. The fresh weight was 46 g for the narrow lens, 37 g for the medium lens, and 17 g for the wide lens. Lettuce growth was restrained under the wide lens because the light was widely spread and its intensity was reduced.

When the driving current was increased to 0.3 A, the fresh weight of lettuce increased to 69 g under the narrow lens and 66 g under the medium lens, but reached only 49 g under the wide lens, a relatively small weight compared to a common leafy lettuce in the market place. The combination of a wide lens and 0.3 A of driving current was still weak and produced lettuces of a similar size to those produced by 0.2 A. There was no significant difference between the fresh weight under the narrow lens and medium lens at this level of current. This result indicates that the amount of light needed to grow lettuces weighing 60 g or more was provided even by the medium lens with sufficient light intensity and that the growth under the narrow lens was reduced under the lower irradiation levels.

For 0.4 A of driving current, the fresh weight produced was 89 g under the narrow lens, 97 g under the medium lens, and 80 g under the wide lens. All three lenses produced lettuces with a fresh weight near 100 g, which is sufficiently large to ship to market. There was no significant difference among the weights; however, the medium lens produced the largest fresh weight and the difference between lenses was minor. The results showed that sufficient light intensity was provided by the diffused light from

Fig. 4 Effect of photosynthetic photon flux distribution on fresh weight of leaf lettuce.

the medium lens, but that the irradiation provided by the narrow lens was not sufficient as the plants grew.

For 0.5 A of driving current, the fresh weight of lettuces exceeded 100 g under the medium lens. The relationship between the lens size and fresh weight was the same as for the 0.4 A driving current. The average size was largest with the medium lens, medium with the narrow lens, and smallest with the wide lens. Although there was no significant difference between the fresh weights, the medium lens did tend to increase the fresh weight. Because electricity consumption in the 0.5 A experimental condition was greater than that for the 0.4 A condition, growth might be expected to promote under the wide light distribution condition, but the relationship of the significant difference

was about the same as with current of 0.4 A. Under the relatively strong light intensities of 0.4 A and 0.5 A (compared with the light intensity of 0.2 A), lettuces achieved a fresh weight of 97.3 g and 105.9 g with the medium lens, and 80.5 g and 87.2 g with the wide lens, respectively. The fresh weight achieved with the wide lens was 18% less than that with the medium lens.

Studies on light distribution has been reported, however most of them relates to the distribution of natural light within plant canopies, as light competition between plant species in plant community (Walker et al., 1988), 3D model and simulation for radiative exchange of various incoming light angular (Chelle and Andrieu, 1998). Very few studies have addressed the problem of the flux distribution of photosynthetic photon flux on horizontal plane. Generally plants respond linearly to light energy, at least at intensities below photosynthetic saturation. Thus, intensity differences can have significant effects on total plant growth and yield, and crop timing (Albright and Both, 1994). In this study, even at the same current value, the growth is different depending on the lens, it is shown that the light distribution also have a significant effect on growth. Woledge (1970) reported that leaves of tall fescue (*Festuca arundinacea* Schreb.) grown in bright light had higher rates of apparent photosynthesis per unit leaf area in bright light, and slightly lower rates in dim light than did those of plants grown in dim light. The plant under narrow lens in our study may have the different rate of photosynthesis per unit area between the center part and outer part of leaves. Therefore, it was clear that there is an optimal flux distribution of PPFD that promotes plant growth, and the lens selection is thought to be involved in the total performance of productivity in plant factories.

Number of leaves

The effect of light flux distribution provided by the difference type of lens on number of leaves in each driving current was shown Fig. 5. The average value of number of leaves was highest under the narrow lens although there was no significant difference between narrow and medium lenses in 0.2 A. The number of leaves under the wide lens was lowest and there was significant difference among the lenses. The tendency of decreasing under the wide lens was the same as the fresh weight. For 0.3 A, the number of leaves under the wide lens was also lowest and the similar tendency was observed. The ratio of dead leaves to all leaves was significantly greater under the narrow lens condition than under the medium and wide lenses. The average number of leaves was highest with the narrow lens, although there was no significant difference between the number of leaves under the narrow and medium lenses with 0.2 A of driving current. The number of leaves with the wide lens was lowest and was significantly different from the number of leaves under the other two lenses. The tendency for the number of leaves to decrease with the wide lens was similar to the tendency of the fresh weight to be lower under this lens.

For 0.3 A, again the wide lens produced the fewest number of leaves. The ratio of dead leaves to total leaves was greatest with the narrow lens and was significantly

Fig. 5 Effect of photosynthetic photon flux distribution on number of leaves of leaf lettuce.

different from the ratio under the other two lenses. There was a significant difference between the narrow and wide lenses, and the number of leaves increased from the narrow to the wide lens. On the other hand, the fresh weight produced under the medium lens was greatest among the three types of lenses, and the fresh weight produced under the medium lens was greater, as shown in Fig. 4, and this tendency is different from that of the number of leaves.

For the 0.5 A condition, there was a significant difference between the narrow and wide lenses, and between the medium and wide lenses, in the number of leaves. The number of leaves was slightly greater for all lens conditions than for the 0.4 A condition. Although the fresh weight with the medium lens was the greatest for 0.5 A in the same manner as 0.4 A, the number of leaves did not repeat this same trend.

Light environment also affects number of leaves in

plants. Sun et al. (2012) showed that leaf number of *Veratrum californicum* was increased by adding supplemental light. Ménard and Dorais (2006) studied the improvement of high pressure sodium (HPS) lamps which is relatively poor in blue and far-red compared to the solar PPFD radiation, and they conducted an experiment using tomato (*Lycopersicon esculentum* 'Trust') and cucumber (*Cucumis sativus* 'Bodega') plants under HPS lamps with or without blue LEDs (455 nm) for 12 or 20-h photoperiods. The number of leaves of cucumber was significantly increased under HPS + blue LED (20-h). These results refer to the fact that the number of leaves influenced by light intensity and quality. A similar effect of light intensity on number of leaves was found in our study. Number of leaves decreased under the wide lens for the 0.2, 0.4 and 0.5 A conditions. This was probably due to the low light intensity under the wide lens conditions.

Stem length

The effect of the type of lens on stem length is shown in Fig. 6. For the 0.2 A condition, the stem length of plants grown under the wide lens was significantly longer than that of plants grown under the other lenses. However, this was thought to be the cause of succulent growth. Although there was no significant difference between the stem lengths under different types of lenses for the 0.3 A condition or the 0.4 A condition, there was a significant difference ($P < 0.05$) between the 0.3 A condition and the 0.4 A condition under the medium lens. No significant difference was observed between the lenses for the 0.5 A condition. Although the stem length for 0.5 A was slightly shorter overall than that for 0.4 A, there was no significant difference between these two current levels with the same lenses. A comparison of the different conditions in the light distribution revealed that stem length was significantly shorter for only the 0.2 A narrow condition ($P < 0.05$). No significant difference was observed in any condition of light intensity with the wide lens.

A previous study reported by Li and Kubota (2009) has shown that stem length of baby leaf lettuce was influenced by the light quality. Stem length increased with cool white fluorescent lamp + far red, and decreased with cool white fluorescent lamp + UV-A and UV-B, respectively. Stem elongation is regulated predominantly by a major active endogenous gibberellin (GA), and GA level in plants is modulated by phytochrome (Weller et al., 1994). Red to far-red light ratios affect activation of phytochrome. Hence, stem length is primarily influenced by light quality. Yanagi et al. (1996) has shown that stem length of lettuce plant was not impacted by light intensity. In our study, a similar result was obtained for 0.3A to 0.5A. Therefore, the stem length was not significantly affected by photosynthetic photon flux distribution created by lens in our conditions.

Growth efficiency

Growth efficiency according to the driving current for each lens is shown in Fig. 7. We define "growth efficiency" as the total amount of power consumed by the LEDs in kWh divided by the fresh weight of lettuces in grams at harvest.

Fig. 6 Effect of photosynthetic photon flux distribution on stem length of leaf lettuce.

Growth efficiency decreases with increasing current value under the narrow lens. This effect occurs because the irradiation range is narrow, and light is concentrated in the central part of the plant. Even when this part of the plant is irradiated with light that is sufficient for growth (0.2 A), under the narrow lens, the outer portion is not sufficiently irradiated. Apparently, even increasing the electric current in this central part of the plant does not promote photosynthesis in the whole plant, and growth efficiency is reduced.

A different trend was found for the medium lens, under which growth efficiency increased as the electric current increased. Growth efficiency reached a maximum value at 0.4 A and was reduced by approximately 15% from that level at 0.5 A. Since a sufficient light intensity was obtained at 0.4 A, increasing the current to 0.5 A wastes light and reduces efficiency. Likewise, under the

Fig. 7 Effect of combination of LED forward current and photosynthetic photon flux distribution on fresh weight of leaf lettuce.

wide lens, although growth efficiency tended to decrease as electric current increased from 0.2 to 0.4 A, the efficiency decreased as the current value increased up to 0.5 A.

Overall growth efficiency with the wide lens was smaller than that under the medium lens. This is because the light was broadly distributed and the PPFD value of the light irradiating the leaves was smaller. A large portion of wasteful light was irradiated outside the plant. The maximum fresh weight was obtained with the medium lens at 0.5 A. In terms of growth efficiency, the maximum growth efficiency (55 g per kWh) was attained with the medium lens and the 0.4 A current value. Clearly, there exists an optimum combination of light intensity (electric current value in this study) and flux distribution to achieve high-growth efficiency. When these factors are combined appropriately, the same input energy can produce higher production efficiency.

CONCLUSION

The growth of lettuce was largely dependent on the light irradiation method (lens size), regardless of the amount of electrical energy expended. When the electric current was at a low level, the growth difference depended on the type of lens, and the fresh weight of the smallest lettuce was only 41% of the fresh weight of the largest lettuce grown under a different lens. Larger current levels did increase the size of the lettuces; the smallest lettuce was 82% of the size of the largest lettuce at 0.5 A. When the current remained constant, the choice of lens increased the fresh weight by 18%. This result regarding fresh weight may provide more information about how to irradiate plants effectively without providing too much light. An effective combination creates a balance between light intensity and light flux distribution (the range of light irradiation). One of the best combinations in our experiment was an electric current of 0.4 A with a lens of FWHM value 13°. The LED chip is small, and its position and the direction of irradiation can be fine-tuned more than ever before. It is possible to develop a technology that can significantly reduce the energy input for plant growth using artificial light irradiation.

To apply our findings to practical use depends on cost. In addition to the lens, some systems use a reflector to concentrate the light beam. It is important to consider the various approaches in order to realize this idea in actual plant factories.

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