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PRODUCTIVITY AND COST PERFORMANCE OF LETTUCE PRODUCTION IN A PLANT FACTORY USING VARIOUS LIGHT-EMITTING-DIODES OF DIFFERENT SPECTRA

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ABSTRACT

Research and development on plant factory technologies has received increasing attention not only in the East, but also in Southeast Asia. Lighting technology using light-emitting-diodes (LEDs) of proper light spectrum improves plant production in a plant factory. What type of LED to be used for certain vegetables and whether it is economically feasible are two questions to be answered by the wide diffusion of the technology. This study intended to answer these questions by conducting an experiment wherein lettuce was grown in a plant factory using seven types of LED of different spectra. The experiment was conducted at Chiba University in Japan from January to March 2017. White LEDs could attain shoot-fresh-weight productivity, comparable to levels attained by fluorescent lamps. However, productivity varied greatly across different LEDs. High productivity LEDs had similar spectrum patterns in terms of percentage shares of photon flux density (PFD) of blue, green, red, and far-red lights, with red color taking about 50% of the entire PFD. At the current market price of lettuce, electricity, and LED lamps in Japan, the cost-performance of all the seven LEDs tested was above the break-even level, although there were large differences in performance between high and low productivity LED lamps.

Key words: Benefit-cost ratio, fresh-weight productivity, light spectrum, percentage shares of PFD

INTRODUCTION

A ‘closed-system’ plant factory is a plant production facility that provides growers with the advantage of complete and precise control of environmental, as well as nutrient factors that are important for plant growth (Kozai and Niu 2016a, Lu et al. 2017). The use of artificial lights in plant factories located in urban areas is a trend among modern agricultural businesses. Research and development in plant factory technologies has attracted the attention of many countries, including Southeast Asian countries, such as Singapore, Thailand, and Vietnam (Nikkei 2016). Many projects are supported by the government of these countries. In a plant factory with artificial lighting, fluorescent lamps have been used as a major light source to produce indoor leafy vegetables for decades until the advent of the light-emitting diode (LED), (Massa et al. 2008). The LED lighting system has many unique advantages over conventional light sources, such as the ability to control spectral composition, to produce very high light levels with low radiant heat output, its specific photosynthetically active radiation (PAR) irradiation, its ease of integration into digital control systems, low electric consumption, and absence of mercury. These advantages have made the replacement of conventional lamps with LEDs a priority area for research (Morrow 2008). Now, many producers of lighting-apparatus are planning to retreat from the production of fluorescent lamps in the view of it containing environmentally-hazardous mercury (Egan 2016, Panasonic 2017). It is virtually mandatory for plant-factory producers to switch from fluorescent lamps to LEDs.

Plant production can be improved by using LEDs of optimum light spectrum. Since plants absorb blue and red lights more efficiently than other colors of light in the visible spectrum (Moss and Loomis 1952), LEDs with blue and red lights (RB-LED) were developed for plant factories. Although efficiency for electrical use of LED that converts electrical energy to photon energy has increased up to 49% (Mitchell et al. 2012, Pinho et al. 2012), the higher investment costs for LEDs than for conventional light sources have been a major barrier in the adoption of LEDs in plant factories. White LEDs have a wider spectrum and are widely used for general lighting in offices, factories, and households. They have become cheaper and will become even cheaper in the near future, due to the rapid increase in demand for such LEDs (Cho et al. 2017). The use of white LEDs for plant production could help the plant-factory system disseminate this widely for effective vegetable production.

The availability of various types of white LEDs have increased rapidly. Although the color of light of these LEDs looks similar, the composition of their spectrum varies. Little is known as to what type of white LEDs is suitable for plant production. Information concerning plant-growth performance of different white LEDs used in plant factories, as well as their cost performance, is of substantial importance for growers in their decision making. With data obtained from seven types of LED used to grow lettuce in a plant factory, we looked into how biological and economic productivity in plant production differed among LEDs.

MATERIALS AND METHODS

Plant material and growth conditions. Lettuce seeds (*Lactuca sativa* L., cv. Frill Ice; Yukijirushi Seed Co., Hokkaido, Japan) were sown in urethane cubes (W 2.3 cm × D 2.3 cm × H 2.7 cm) and placed under dark conditions at 20 °C for 48 h. Seedlings were grown in an environment-controlled growth chamber under cool white fluorescent lamps (Panasonic FHF32EX-N-H) at a photon flux density (PFD) of 150 µmol m^{-2} s^{-1} for 16 h d^{-1}. After 12 days of sowing, uniformly-sized plantlets were transplanted into polystyrene panels (144.4 plant m^{-2}) and cultivated under seven types of LED lamps at a PFD of 200 µmol m^{-2} s^{-1} for 14 h d^{-1}. After 23 days of sowing, the plantlets were spaced (33.3 plants m^{-2}) and cultivated under the same light conditions until harvest (35 days after sowing). Plants from all treatments were hydroponically grown through the deep flow technique. Growth conditions throughout the experiment are summarized in Table 1.

Table 1. Growth conditions of lettuce harvested at 35 days after sowing.

Condition	Seedling (12 days)		After transplanted (23 days)	
	Light	Dark	Light	Dark
Air temperature (°C)	25	20	25	20
Relative humidity (%)	45	65	45	65
CO_2 concentration (µmol mol^{-1})	1,200	1,200	1,200	1,200
Light source	Fluorescent lamp	-	LED lamp	-
Photoperiod (h)	16	8	14	10
PFD (µmol m^{-2} s^{-1})	150	-	200	-
Nutrient solution [a]	EC=1.8 dS m^{-1}		EC=2.4 dS m^{-1}	

* EC represents Electrical Conductivity. The Enshi formula was used throughout the plant growth period of 35 days (further details of the Enshi formula can be found in Asao et al. 2013).

Light treatments, sampling method, and measurements. Seven types of LEDs with different spectra were used, wherein six were white LEDs while one was red+blue (Table 2).

Table 2. Proportions of photon flux density (PFD) of seven LED lamps in the entire wavelength band (380-780 nm)

	PFD Ultra violet (380-399nm)	PFD Blue (400-499nm)	PFD Green (500-599nm)	PFD Red (600-699nm)	PFD Far-red (700-780nm)
	……		%	……	
LED-A [1]	0.0	7.5	28.4	51.5	12.5
LED-B [1]	0.3	13.0	24.2	52.3	10.3
LED-C [1]	0.0	13.2	34.3	43.7	8.7
LED-D [2]	0.0	15.8	10.9	63.9	9.4
LED-E [2]	0.0	12.2	21.7	58.5	7.5
LED-F [1]	0.0	26.3	40.7	29.8	3.2
LED-G [3]	0.0	20.7	0.5	77.5	1.2

[1] White LED (single-chip+phosphor). [2] White-LED (red-blue-green LED). [3] Non-white-LED (red-blue LED).

Of the six white LEDs, four were single-chip-plus-phosphor LEDs while two were red-blue-green LEDs (Cho et al. 2017). For all the LEDs, PFD was adjusted to 200 ± 10 μmol m^{-2} s^{-1} at the surface of the cultivation panel with a light sensor (Licor 250A; Li-cor Inc., Lincoln, NE, USA) for all treatments or LED types. The spectra were measured by a spectroradiometer (Lighting Passport, AsenseTek, Taiwan). The lettuce was harvested at 35 days after sowing. Shoot fresh weight was measured immediately after harvest from the cultivation area. The experiment was repeated twice, wherein eight were sampled for measurements after the first experiment while six were sampled after the second. A fluorescent lamp was not chosen as a light treatment because fluorescent lamp production would completely stop in the near future.

Estimation of cost performance. The economic feasibility of replacing conventional light sources with LEDs in plant factories was examined by evaluating profitability by means of the benefit-cost ratio, which was defined as follows:

$$(B/C)_i = (1-\alpha)\, P_o\, Y_i \,/\, [P_e\, (kWh)_i + I_i\,/LS + r\, I_i] \qquad [1]$$

where $(B/C)_i$ = benefit-cost ratio of i-th-LED (i = A, B, C, …, G), α = the percentage share for total current production costs of lettuce, excluding electrical power costs for lighting and investment costs for LED, P_o = price of output (lettuce) in US\$ kg^{-1}, Y_i = lettuce yield = total shoot fresh weight (kg m^{-2}) of the i-th LED, P_e = price of electricity (US\$ kWh^{-1}), $(kWh)_i$ = electric power used for lighting with the i-th LED (kWh m^{-2}), I_i = investment cost of the i-th LED (US\$ m^{-2}), LS = life-span of LEDs (number of crops), and r = interest rate (% per crop growing duration). By definition, if $(B/C)_i > 1$, lettuce production with the i-th LED is economically feasible, and the higher the B/C ratio, the higher the economic profitability.

The total shoot fresh weight produced by the i-th LED, Y_i, was expressed as the mean fresh weight from the total shoots of lettuce. Of the total electricity consumption needed to produce Y_i, $(kWh)_i$, the rate of the LEDs' electrical consumption was calculated using the energy of photons emitted by the LEDs during cultivation divided by the electro-optical conversion rate of the LED. The energy of photons was calculated according to Planck's equation based from the light spectrum. The conversion rate from LED electrical energy to photosynthetically-active radiation energy was assumed to be 0.5 (Kozai and Niu 2016b). The electric consumption of fluorescent lamps for seedlings was based on the rating of the fluorescent lamps used. The percentage share of the total current production cost, not including costs for electricity, LED's depreciation, and interests, was assumed to be one-third of the total value of fresh weight produced (Tsuchiya 2012). The items

included in this current cost were seeds, fertilizers, chemicals, labor, and other consumable goods. Prices from their respective markets in Tokyo, Japan, at the time of the experiment (2017) were used for prices of lettuce (P_o = US$ 10 kg^{-1}) and electricity (P_e = US$ 0.3 kWh^{-1}). Since not all LED lamps used in the experiment were available in the market at that time, the investment cost for LED lamps were assumed to be I_i = I = US$ 273 m^{-2}, based on the median price for LED lamps in the market in 2017, which was US$ 54.5 per lamp (6000 yen; US$ 1.0 = 110 yen). Five LED lamps per m^2 were used in the experiment. The life-time of LEDs (LS) was assumed to be 155 crops for all LEDs, which was obtained by dividing the company-stated life span of the LED (50,000 hours) by the lighting hours per crop (322 hours) from the experiment. The interest rate varied greatly among countries, with Japan being the lowest in the world (World Bank 2017). During this study, the mean world interest rate was 12% per year (World Bank 2017), while the interest rate of World Bank for development projects was assumed to be 1.09% per 35 days (= 1 - $1.12^{35/365}$).

Although fluorescent lamps were not tested in this study, its cost performance was estimated by assuming the highest lettuce yield obtained in the experiment. The highest yield from our experiment is comparable to, or higher than, the highest yield attained from previous studies which grew lettuce using artificial lighting. Based on necessary electric power to obtain the same PFD by 7 lamps per m^2, the electricity consumption of fluorescent lamps was calculated to be 1.7 times that of LEDs. Other assumptions were: lifetime = 25,000 hours while investment cost = US $ 210 m^{-2}. As a conventional lighting source, the B/C ratio of fluorescent lamps was expected to be more than unity. The point of estimation was to assess how the cost performance of fluorescent lamps was compared with that of LEDs.

To examine how sensitive LEDs' cost performance was with respect to changes in market price and depreciation costs of LEDs, the B/C ratios of LEDs were estimated by changing a price parameter (P_o, P_e, or I_i in Equation [1]), while fixing other prices at their market levels.

RESULTS AND DISCUSSION

Fresh-weight productivity

The fresh weight of lettuce shoots was 2.55 kg m^{-2} if averaged over the seven LEDs, or 2.66 kg m^{-2} if averaged over the six white LEDs (Table 3, Column [1]). This level of yield, or productivity, per unit area planted with lettuce from the plant factory containing white LEDs was comparable to that of non-headed lettuce produced in plant factories using conventional fluorescent lamps. Tsuchiya (2012) reported that the yield of non-headed lettuce of a commercially-operated plant factory using fluorescent lamps was 2.5 kg m^{-2}, which is similar to that obtained from our study. After reviewing a large number of experiments, Kozai and Niu (2016c) found that the yield of lettuce leaves in closed plant factory systems ranged from 2 to 3 kg m^{-2}. As far as yield per unit area of 'one layer' was concerned, the productivity of non-headed lettuce in a plant factory was comparable to that of the production of headed lettuce under ordinary outdoor cultivation. The average yield of headed lettuce by Japanese farmers from 2010–2014 was 2.3 kg m^{-2} (2.3 t ha^{-1}) during winter, 2.6 kg m^{-2} in spring, and 3.0 kg m^{-2} in summer-autumn (MAFF 2017). Cultivation of up to 10 layers on a given ground area, coupled with shorter growing periods, can result in about 100 times higher productivity in plant factory production compared to ordinary outdoor cultivation.

Lettuce yield varied significantly across treatments (LEDs), (Table 3, Column [1]). The LEDs used were classified into three groups in terms of fresh-weight productivity: high, medium, and low productivity groups. It should be noted that the yields of two white-LEDs belonging to the high productivity group (LED-A and LED-B) were high, higher than the upper-end from the yield range provided by Kozai and Niu (2016c). The non-white LED (LED-G) was least productive, with yield closer to the lower-end of the same yield range as above.

The LEDs' electric consumption varied across treatments, with the degree of variation much less than that of fresh weight (Table 3, Column [2]). As a result, the pattern of variation in fresh-weight productivity per kWh almost followed the same pattern as that of fresh-weight per m^{-2} (Table 3, Column [3]). It was suggested that the productivity per kWh of fluorescent lamps was similar to that of LED-G.

Table 3. Shoot fresh weight of lettuce grown for 35 days with LED, LED's electricity consumption, fresh-weight productivity per kWh, and B/C ratio evaluated at the market prices.

	Fresh weight [1]	Electricity consumption [2]	Productivity [3]=[1]/[2]	B/C ratio [4]
	(kg m^{-2})	(kWh m^{-2})	(g kWh^{-1})	
LED-A	3.26 a	16.5	198	2.21
LED-B	3.21 a	16.7	192	2.15
LED-C	2.62 b	16.4	160	1.74
LED-D	2.40 b	17.8	135	1.62
LED-E	2.35 b	17.0	139	1.59
LED-F	2.12 c	16.4	129	1.37
LED-G	1.92 c	16.4	117	1.30
Mean	2.55	16.7	152	1.71
Fluorescent lamp	3.23	29.6	109	1.57

[1] For LEDs, the means of 15 replications. Figures followed by the same alphabet are not statistically different at $p < 0.01$ (multiple comparison by Tukey). For fluorescent lamp, the average fresh weight of the top productivity group was assumed.

[2] Obtained by dividing the energy of photons emitted by LEDs during the cultivation period by the electro-optical conversion rate of LED. The energy of photons was calculated according to Planck's equation based on the light spectrum data of each LED lamp and the conversion rate from LED electrical energy to photosynthetically active radiation energy was assumed to be 0.5. The electricity consumption of fluorescent lamps was assumed to be 1.7 times higher than that of LEDs.

[4] Estimated by Equation [1] at the prevailing market prices for lettuce, electricity, and LED (or fluorescent lamp).

Correlation analysis between fresh weight and LEDs' spectrum characteristics showed that the proportion of far-red light in the entire PFD had the highest positive correlation with fresh weight (Table 4). The correlation coefficient for blue light was negative and significant, while the correlation coefficient of red light was not significant at $p = 0.05$. The ratio of red to blue light correlated positively with fresh weight. The ratios of red to green and red to far-red were also significantly and negatively correlated with fresh weight. LED-G, being blue-red and the least productive, was scarcely endowed with green and far-red lights (Table 2).

Such results imply that the balanced distribution of red and blue lights in the spectrum, with 50% of red in the entire PFD, rather than absolute levels of PFD, was important in determining shoot fresh weight (Tables 2 and 4). Some studies suggest that the far-red, not its absolute level, but its balance with lights from other wavelength bands, played certain roles in increasing fresh weight (Kubota et al. 2012, Meng and Runkle 2017). It was also suggested that green light, which had been considered as playing a small role in plant growth, played positive roles, especially under dense planting cultivation (Lu et al. 2012, Massa et al. 2008). Further studies are required to optimize the type of white LED of a specific spectrum on the growth of specific vegetables.

Table 4. Simple correlation coefficient (n = 105) between shoot fresh weight m^{-2} and the proportion of PFD in the wavelength band of blue, green, red, and far-red, and between shoot fresh weight m^{-2} and the ratios of red to blue, green, or far-red.

	Percentage share of PFD				Ratio between the shares		
	Blue	Green	Red	Far-red	Red/ Blue	Red/ Green	Red/ Far-red
Correlation coefficient	-0.665	0.283	-0.188	0.760	0.526	-0.465	-0.514
Significance level[a]	**	**		**	**	**	**

[a] ** means that the null hypothesis of no correlation is rejected at $p < 0.01$ (two-tail test). The correlation coefficients at the critical levels of significance for n = 105 are 0.192 at p = 0.05 and 0.250 at p = 0.01.

Cost performance by LED

At price levels prevailing in markets in Tokyo, Japan (P_e=0.3, P_o=10, and I=273), the B/C ratio of lettuce production was more than unity for all seven LEDs (Table 3, Column [4]). This indicated that the cost performance of lettuce production in plant factories with white LED lamps was above the break-even level, and that the shift of lighting source in plant factores from fluorescent to white LED lamps was economically feasible under present technological and economic conditions. However, performance varied considerably among the different white LEDs. B/C ratio of the LED lamp of the highest cost-performance was higher than that of the lowest ost-performance LED lamp by as much as 70%. As expected, the B/C ratio of fluorescent lamps was also more than unity (Table 3, Column [4]). It was suggested, however, that its cost-performance was at a level similar to the level attained by LED-E, a white-LED from the medium productivity group, and that there were many white-LEDs with better cost-performances than fluorescent lamps.

Results of the sensitivity analysis revealed that electric price would not be a serious barrier in the introduction of white-LEDs (Fig. 1, Panel A). Even if electric price was raised to more than three times higher than present levels, the B/C ratio of the two white-LEDs from the high-productivity group would remain more than unity. A World Bank database showed that electric price was highest in Japan among major countries (Fig. 2). Although no clear trend was found in terms of electric price among countries and regions, electric price was lower by about 50% in Southeast Asian countries than in Japan. A lower electric price would improve cost performance from the current level.

Cost performance was sensitive to changes in lettuce price (Fig. 1, Panel B). A decline in output price by 55%, with the other two prices remaining at same levels, would deprive LEDs in the high-productivity group of economic feasibility. In Southeast Asian countries, such as Thailand, Malaysia, and Indonesia, lettuce price was lower than prices in Japan by about 50% (NUMBEO 2017). However, electrical costs in these countries, which were lower than Japan by about 50%, would cancel out the decline in cost performance. Similarly, investment costs, *i.e.*, cost of LED lamps, would not create any barrier in switching light source to white LEDs in the lettuce production in plant factory (Fig. 1, Panel C). Any downward change in this cost would increase the profitability of lettuce production from the present level. Every decade since the advent of LEDs in the early-1990s, the price of LEDs has been declining geometrically to a level one-tenth of the level in the previous decade (Cho et al. 2017). The price decline of white LEDs would continue, as the production increases to satisfy rapidly increasing demand for replacing fluorescent lamps in all spheres of human life.

The profitability would further increase by mixed use of different types of LED in different plant growth stages. For instance, it can be an alternative lighting recipe to attain a higher productivity to use LED-B for high plant biomass and LED-C for low tip-burn occurrence from 12 days after sowing. Another possibility to increase the cost performance is to improve plant quality as well as

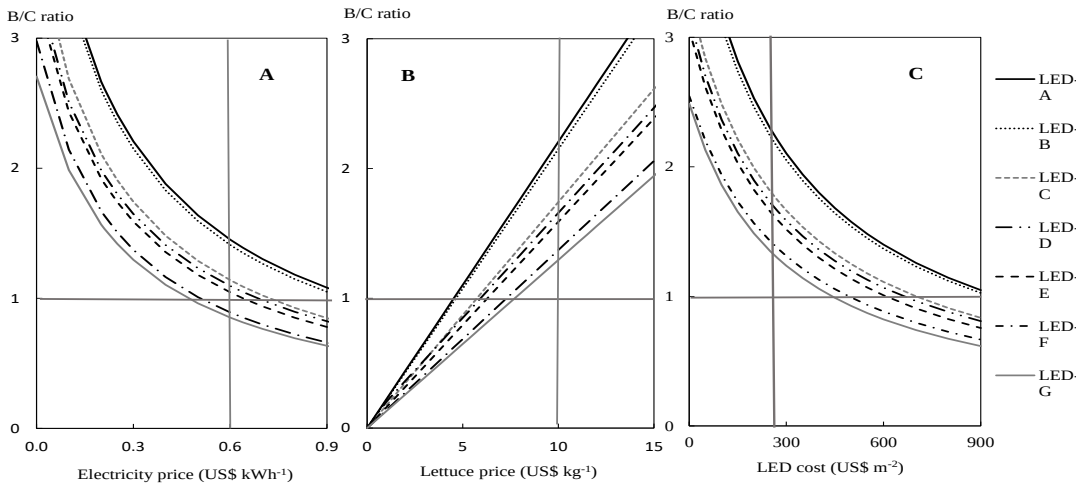

Fig. 1. Sensitivity analysis: changes in cost performance of different LED lamps used for lettuce production at 200 µmol m-2 s-1 PPFD, measured by the Benefit-Cost ratio defined as per Equation [1], for different levels of lettuce price (Po), electricity price (Pe), and LED cost (Ii), with the prevailing market prices for the non-varying prices (Po = US$ 10 kg-1; Pe = US$ 0.3 kWh-1; and Ii= US$ 273 m-2).

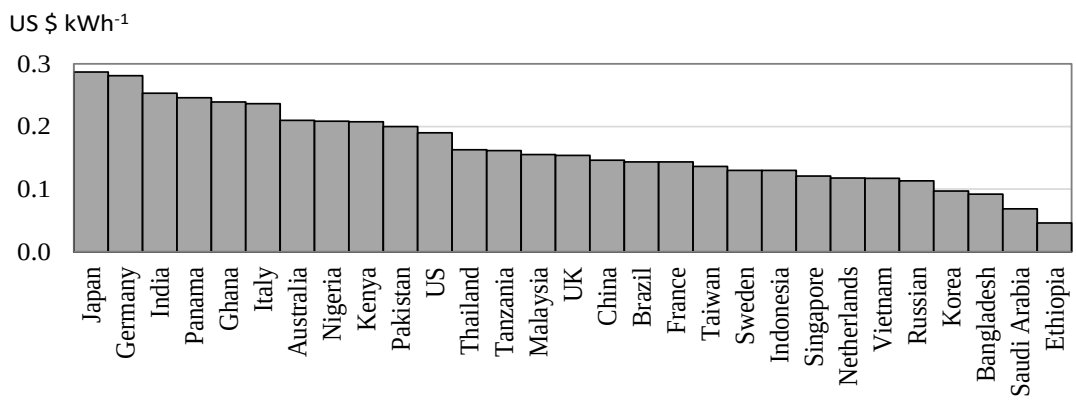

Fig. 2. Electricity price in selected countries, 2014-2016 average. Source: Arlet (2017)

quantity. Monochromatic lighting has been proven to increase plant quality. Blue LED increased chlorogenic acid greater than red LED (Johkan et al. 2010), green LED as a supplemental light increased anthocyanin in lettuce leaves (Samuolienė et al. 2013), or blue LED increased ascorbic acid greater than red+blue light (Amoozgar et al. 2017). The use of these different types of LED is another important option for the closed plant production system. Finally, it should be noted that other resources used in the closed production system, *e.g.*, water, CO_2, and fertilizer, not considered in this study, need to be examined for attaining the overall resource-use efficiency (Kozai 2013).

CONCLUSION

The replacement of light sources from fluorescent lamps to white LEDs in the closed plant production system is feasible, both economically and technologically. The use of white LEDs for plant production in a plant factory could produce as much biomass could be produced with fluorescent

lamps. There are white LEDs that are better than fluorescent lamps in the cost performance as well as the fresh-weight productivity. The fresh-weight productivity per m^2 varied considerably across LEDs tested, depending on the composition of their spectra. Since there will be a wide variety of white LEDs available for use in plant factory production, research is urgently needed on type of white LEDs with specific spectrum that would work best for specific vegetables. Lettuce production using white LEDs is economically feasible under present technological and economic conditions. The use of white LEDs in lettuce production in plant factories could be an economically feasible production option not only in Japan but also in other countries, including Southeast Asia.

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