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Study of Plant Cultivation Using a Light-Emitting Diode Illumination System to Control the Spectral Irradiance Distribution

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Abstract

In plant cultivation, the number of photons is more important than the light energy from the chemical reactions that occur during photosynthesis. In addition, the blue and red photon flux (B/R) ratio is an important parameter for plant cultivation. Here we discuss the effect of the spectral irradiance distribution and the B/R ratio on plant cultivation. We cultivated lettuce seedlings, *Lactuca sativa* L. Cv. Okayama, using a light-emitting diode illumination system that can precisely control the spectral irradiance distribution and B/R ratio. The B/R ratio varied from 0.36 to 2.06 according to the intensity of the blue light when the photosynthetic photon flux density values were sufficient to ensure the 150 - 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$. High photon flux densities of blue light result in reduced plant length, plant height, and leaf area, thereby suggesting its role in the suppression of leaf growth. Therefore, we conclude that a lower photon flux of blue light (B/R Ratio) is optimal for lettuce cultivation.

Keywords

Plant Cultivation, LED Lighting, Blue and Red Photon Flux (B/R) Ratio

1. Introduction

Plant factories have many advantages, *i.e.*, the plants' growth environment (e.g., light, temperature, humidity, carbon dioxide concentration, moisture, and nutrients) can be controlled. Therefore, the high-quality planned production of plants can be achieved. There are two types of plant factories. One uses sunlight and another uses only artificial light. In this study, we focused on plant cultivation using only artificial light because it does not depend on the weather and can be available in indoor spaces and/or in narrow spaces. There are several types of light sources for plant cultivation such as high-pressure sodium lamps, metal halide lamps, fluorescent lamps, and light emitting diodes (LEDs) [1]. The use of LEDs in plant cultivation has recently attracted attention due to a number of advantages: (1) it is possible to precisely control the emission wavelength; (2) their power consumption is smaller than that of other light sources, such as incandescent and fluorescent lamps; and (3) they are capable of pulse irradiation, which is an advantage in plant photosynthesis. Mori *et al.* reported that the growth rate of *Lactuca sativa* cv. "Natsuyo-Samdana" with pulse irradiation is higher than that with continuous irradiation [2]. The chemical reaction in photosynthesis is as follows

$$H_2O + CO_2 \rightarrow 1/6\, C_6H_{12}O_6 + O_2 \tag{1}$$

The reaction in Equation (1) depends on the number of photons. The action spectrum of photosynthesis was first reported by McCree [3] [4]. Photons contribute to the generation of glucose, which determines the rate of photosynthesis. Plants require visible light within a wavelength range of 400 - 700 nm to promote photosynthesis and growth [3] [4]. In particular, blue and red light wavelengths are necessary because they are absorbed by chlorophyll. In general, blue light is helpful for morphological changes, whereas red light facilitates photosynthesis [5] [6]. In addition, Terashima *et al.* reported the role of green light in photosynthesis [7]. Moreover, Fujiwara *et al.* reported plant cultivation using LEDs of five peak wavelengths (405 nm, 460 nm, 630 nm, 660 nm, and 735 nm) [8]. From these two reports, it can be seen that green light is necessary for plant cultivation [7]. In plant cultivation, the number of photons is more important than the light energy due to the chemical reactions that occur during photosynthesis; photons contribute to generating glucose, which determines the rate of photosynthesis. Therefore, the photosynthetic photon flux density (PPFD), which is the number of photons in the wavelength range of 400 - 700 nm, is often used. It is obtained from the spectral irradiation $E(\lambda)$ ($W \cdot m^{-2} \cdot nm^{-1}$)of the lighting system mentioned below [4]:

$$\text{PPFD value}\left(\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}\right) = \frac{1}{120}\int_{400}^{700} E(\lambda)\lambda \mathrm{d}\lambda \tag{2}$$

In addition, the blue and red photon flux (B/R) ratio is an important parameter for plant cultivation. Each plant species would have different optimum B/R ratio, even though few studies have reported on the relationship between plant cultivation and the B/R ratio. In our previous studies, this relationship was studied using a fixed spectral irradiance distribution with different B/R ratios, such as high-intensity discharge lamps and LED lights [9]. We found that it was possible to suppress leaf extension with a high photon flux density of blue light; however, the plants' leaves became hard and their thickness increased. Therefore, it is clear that controlling both the spectral irradiance distribution and the B/R ratio is very important. Based on the above results, in this study, we cultivated plants using an LED illumination system that could precisely control both the spectral irradiance distribution and the B/R ratios to examine their effects on plant cultivation.

2. Characterization of the LED Lighting System

The LED illumination system, measuring 500 × 350 mm^2, was composed of surface-mounted LED arrays of blue, green, and red, as shown in **Figure 1**. The power consumption was 140 W. The green and red LEDs were fabricated using blue LEDs and phosphors. The LED peak intensity of three kinds of lights could be adjusted from 0% to 100%, independently. The dominant wavelengths of the red, green, and blue LEDs were 660 nm, 550 nm, and 460 nm, respectively.

The pulse frequency was kept constant at 2 kHz and the duty ratio of the on-pulse could be varied from 0.3 to 0.7 (period: 500 μsec, on-pulse time 150 μsec - 350 μsec). The intensity of pulse could be adjusted independently.

The spectral irradiance distribution was measured using an optical fiber and a monochrometer. The distance (d) between the surface of the LED lighting system and the tip of the optical fiber was set between 150 mm and 250 mm to obtain PPFD values measured by JIS (Japanese Industrial Standards) lighting average method using light meter and quantum sensor (LI-250A and LI-190R, LI-COR, inc.) of 150 - 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$. The illumination conditions are listed in **Table 1**. The intensity of the blue LED (B) varied from 10% to 100%, whereas that of the green LED (G) varied from 40% to 100%, and that of the red LED (R) was constant for all conditions to control B/R ratio by only the photon flux of blue light. For all conditions, the on-pulse time was 350 μsec. For condition 4, the photon flux of green light decreases to reduce the photon flux of the blue light.

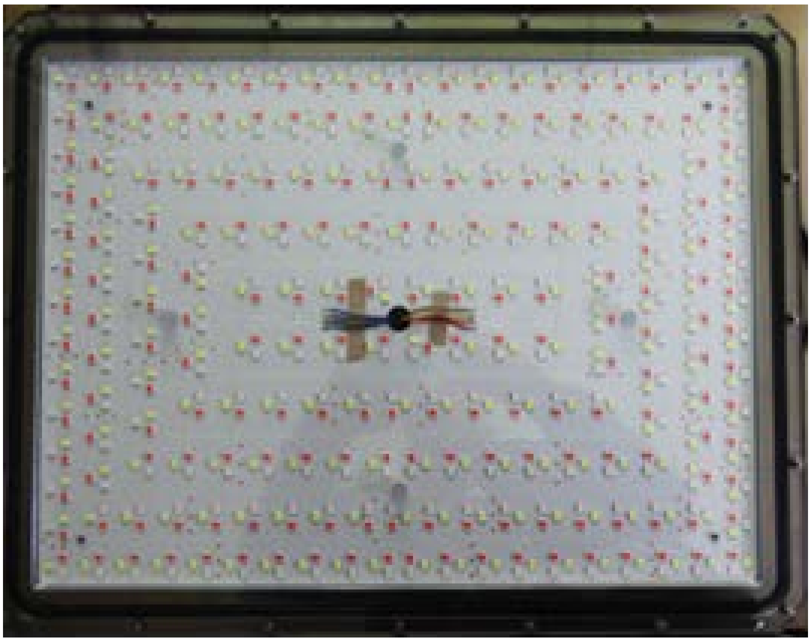

Figure 1. Top view of the LED illumination system.

Table 1. Illumination conditions.

#	Illumination Conditions (For all conditions, R = 100%)	Photon flux for blue light ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	Photon flux for red light ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	B/R ratio	PPFD value ($\mu mol \cdot m^{-2} \cdot s^{-1}$)
1	G = 100%, B = 100%, d = 150 mm	216.5	104.9	2.06	415.9
2	G = 100%, B = 100%, d = 250 mm	132.3	75.3	1.76	271.8
3	G = 100%, B = 20%, d = 150 mm	46.9	76.0	0.62	186.3
4	G = 40%, B = 10%, d = 150 mm	32.5	90.1	0.36	167.6

Figure 2 shows the spectral irradiance distribution at the center of the cultivation area. From the spectra, we can see that, when the intensity of the blue light decreased, the spectral irradiance value also decreased. From these spectra and the PPFD value, the value of the red and blue photon fluxes and the B/R ratio can be calculated, as shown in **Table 1**.

Therefore, the B/R ratio changed from 0.36 to 2.06 depending on the intensity of the blue light. Moreover, **Figure 3** shows the distributions of the PPFD value for condition #1 and #4. The PPFD values were almost sufficient to achieve the 150 - 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$, which is required to cultivate the plants [10]. For each case, the PPFD value, which is larger than 150 $\mu mol \cdot m^{-2} \cdot s^{-1}$ is maintained in the cultivation area. However, there are some peaks of PPFD value because of the differences in PPFD values at the center and the edge area due to the distribution of the illuminance of each LED. Therefore, it is necessary to improve the distribution of the PPFD value.

3. Discussion of Plant Cultivation Using the LED Illumination System

In this study, we cultivated lettuce seedlings of *Lactuca sativa* L. cv. Okayama. The distance between the LED illumination device and the plants was 250 mm. The lighting conditions are shown in **Table 1**. For all the conditions, the LED lights illuminate the lettuce for 24 hours per day. The temperature of the cultivation area is almost 20˚C and the humidity is about 50%. We measured leaf number (longer than 1 cm) and the area of whole leaves using scanned images, stem lengths, stem diameters, plant heights, and plant lengths by destructive measurements. Measurements were obtained on day 1, which was the first day of light exposure, as well as on days 8, 12, and 15. The period of seedling rising is 12 days. **Figure 4** shows photos of the leaves for conditions #1 and #4. The results demonstrate that high photon flux densities of blue light led to a reduction in plant length and leaf area, therefore suppressing leaf growth.

Next, the changes in the plants' fresh mass, dry mass, leaf number and area, stem length and diameter, and plant height and length were characterized. **Figure 5** shows the measurement results of the plant length, plant height, and leaf area. On day 15, the leaf area, plant length, and plant height were reduced for greater blue photon flux densities. When the blue photon flux density was excessive, the growth of the leaves was suppressed. The amount of blue photons in the photon flux density has a large influence on the suppression of leaf growth. A

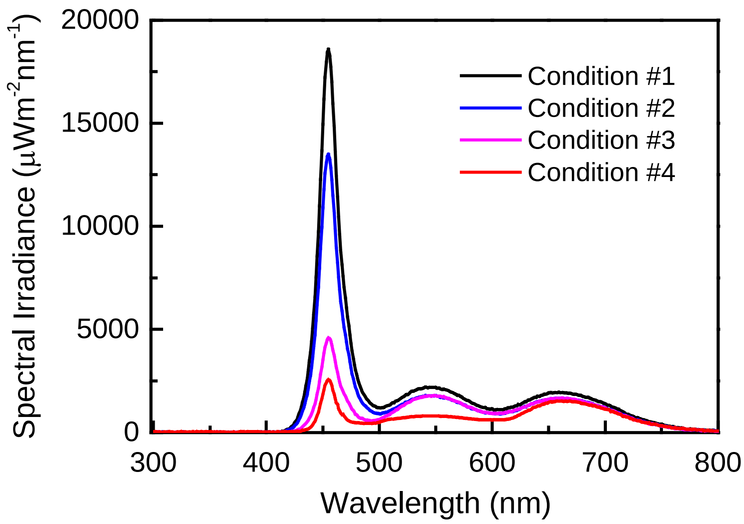

Figure 2. Spectral irradiance distribution at the center of the cultivation area.

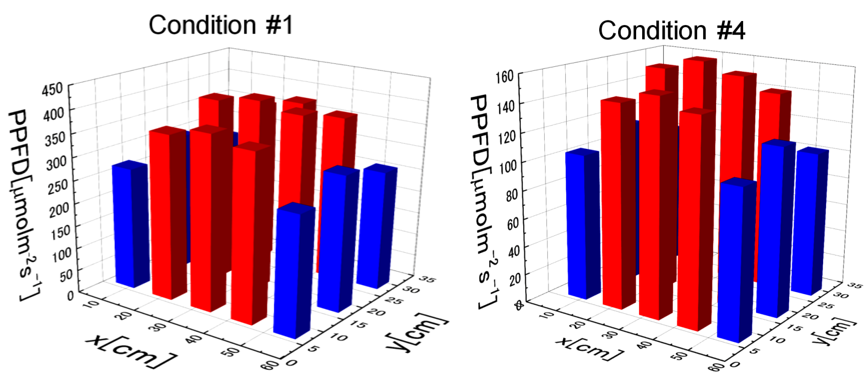

Figure 3. The distributions of the PPFD value for condition #1 and #4.

t-test, a type of statistical method, with a significance level of 5% demonstrated a significant difference in the measurement result for the leaf area on day 15 for conditions #1 and #4 using 5 samples in a staggered manner considering the dispersion of the respective PPFD values. In addition to the leaf area, there were also significant differences in the measurement results in terms of plant length, and plant height.

Conversely, Figure 6 shows the measurement results for the stem length, stem diameter, and leaf number. On day 15, the stem diameter was greater for increased blue photon flux densities; however, the stem length and the leaf number did not have a difference as clear as the B/R ratio. When the amount of blue photon flux density is insufficient, stem growth is suppressed. The amount of blue photons in the photon flux density will therefore affect the stem growth. From these results, it is thought that a high photon flux density of blue light leads to a reduction in the plant length, plant height, and leaf area, therefore suppressing leaf growth. Similar results were obtained by Oshima *et al.* in the cultivation of red-leaf lettuce [10]. Therefore, we conclude that a lower photon

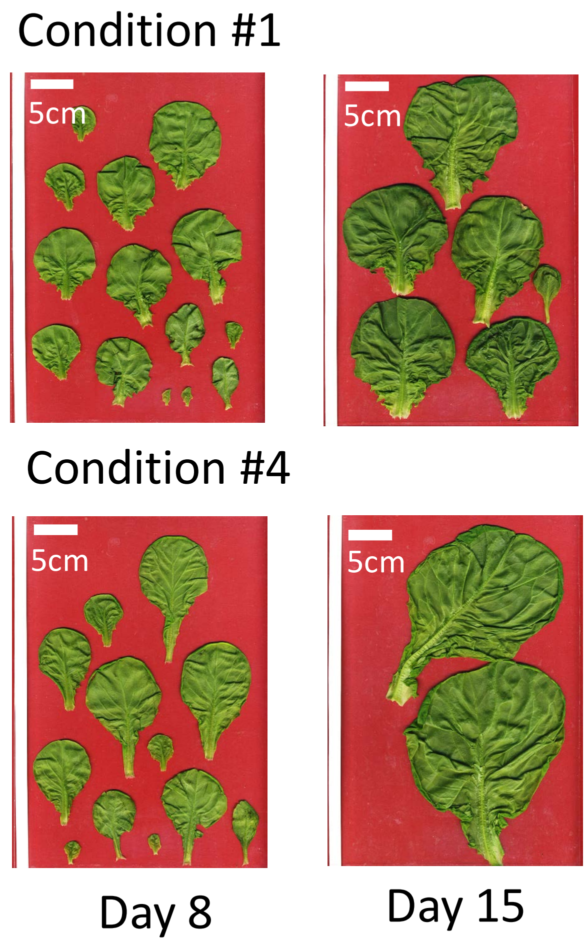

Figure 4. Photos of the leaves for conditions #1 and #4.

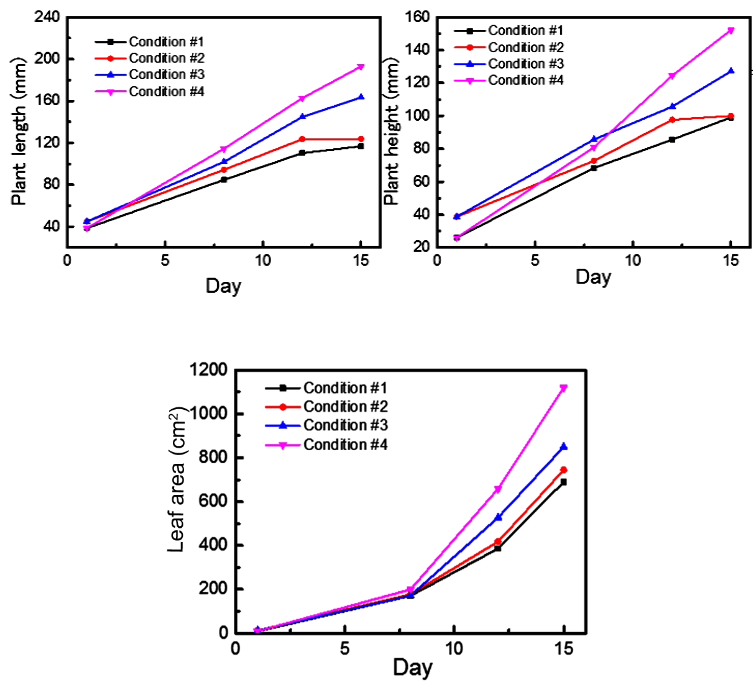

Figure 5. Measurement results for the plant length, plant height, and leaf area.

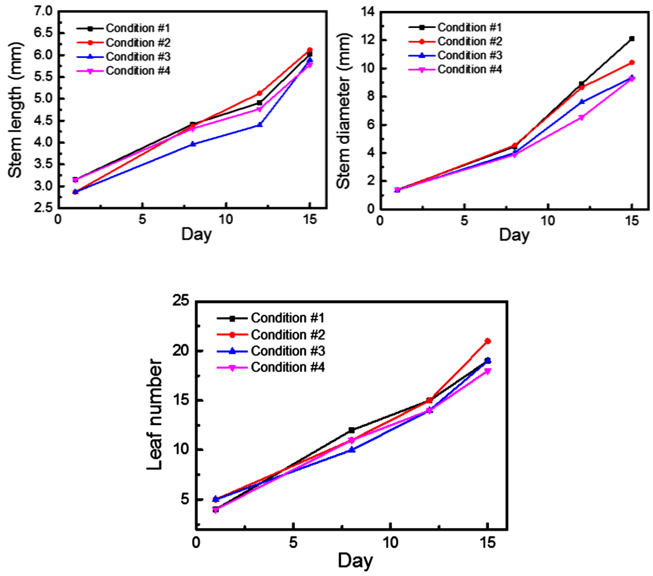

Figure 6. Measurement results for the stem length, stem diameter, and leaf number.

flux of blue light (B/R ratio: 0.3 - 0.6) is optimal for lettuce cultivation. Furthermore, in this study, to decrease the photon flux of blue light, the intensity of green light was decreased. However, the effect of the green light must be considered in the future. This study was carried out in the perfect artificial cultivation; however, these results can be extended to outdoor cultivations.

4. Conclusion

In this study, we discussed the effects on plant cultivation of the spectral irradiance distribution and the B/R ratios, which we precisely controlled using an LED illumination system. The B/R ratio varied from 0.36 to 2.06 according to the intensity of the blue light. The PPFD values were sufficient to ensure the 150 - 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ required to cultivate the plants. The lettuce was then cultivated using this LED illumination system. When the photon flux density of the blue light was high, the plant length, plant height and leaf area were reduced. Therefore, a high blue light photon flux density suppresses leaf growth. Because we used blue LEDs in the illumination system, the B/R ratio which is less than 0.36 is not realized; therefore, we conclude that there is an optimum condition, particularly lower B/R ratio, for lettuce cultivation.

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References

[1] Bula, R.J., Morrow, R.C., Tibbitts T.W., Barta D.J., Ignatius R.W. and Martin T.S.

(1991) Light-Emitting Diodes as a Radiation Source for Plants, *HortScience*, **26**, 203-205.

[2] Mori, Y., Takatsuji, M., and Yasuoka, T. (2002) A Effects of Pulsed White LED Light on the Growth of Lettuce. *Journal of Society of High Technology in Agriculture*, **14**, 136-140. (in Japanese)

[3] McCree, K.J. (1972) The Action Spectrum, Absorptance and Quantum Yield of Photosynthesis in Crop Plants. *Agricultural Meteorology*, **9**, 191-216. https://doi.org/10.1016/0002-1571(71)90022-7

[4] McCree, K.J. (1972) Test of Current Definitions of Photosynthetically Active Radiation against Leaf Photosynthesis Data. *Agricultural Meteorology*, **10**, 443-453. https://doi.org/10.1016/0002-1571(71)90045-3

[5] Britz, S.J., and Sager, J.C. (1990) Photomorphogenesis and Photoassimilation in Soybean and Sorghum Grown under Broad Spectrum or Blue-Deficient Light Sources. *Plant Physiology*, **94**, 448-454. https://doi.org/10.1104/pp.94.2.448

[6] He, J., Qin, L., Chong, E.L.C., Choong, T.-W. and Lee, S.K. (2017) Plant Growth and Photosynthetic Characteristics of Mesembryanthemum Crystallinum Grown Aeroponically under Different Blue- and Red-LEDs. *Frontiers in Plant Science*, **8**, 361. https://doi.org/10.3389/fpls.2017.00361

[7] Terashima, I., Fujita, T., Inoue, T., Chow, W.S. and Oguchi, R. (2009) Green Light Drives Leaf Photosynthesis More Efficiently than Red Light in Strong White Light: Revisiting the Enigmatic Question of Why Leaves are Green. *Plant Cell Physiology*, **50**, 684-697. https://doi.org/10.1093/pcp/pcp034

[8] Fujiwara, K., Yano, A. and Eijima, K. (2011) Design and Development of a Plant-Response Experimental Light-Source System with LEDs of Five Peak Wavelength. *Journal of Light* & *Visual Environment*, **35**, 117-122. https://doi.org.10.2150/jlve.35.117

[9] Motoagito, A., Yamamoto, T., Hiramatsu, K. and Murakami, K. (2014) Plant Cultivation by Using White LED Lamp and HID Lamp. *Proceedings of the* 2014 *Annual Conference of the IEIJ*, Saitama, 4-6 September 2014, 9-3. (in Japanese)

[10] Oshima, T., Ohashi-Kaneko, K., Ono, E. and Watanabe, H. (2015) Determination of Optimum Red and Blue Lighting Conditions for Production of Red-leaf Lettuce Cultured under LEDs. *Journal of Society of High Technology in Agriculture*, **27**, 24-32. (in Japanese) https://doi.org/10.2525/shita.27.24