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Estimation of supplemental lighting efficiency based on PPFD distribution on the canopy surface

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Abstract

Criteria for evaluation of the efficiency of supplemental lighting based on photosynthetic photon flux density (PPFD) distribution on a canopy surface under artificial light were proposed, and the possibility of a reflection-image-based estimation of PPFD distribution on the canopy surface was discussed. Reflection images of plant canopy surfaces under various artificial lighting conditions were acquired from three directions with a digital camera equipped with a blue-green band-pass filter. PPFD was measured at one point on the canopy by a quantum sensor simultaneously with imaging, and the result was used to determine a regression model to estimate PPFD on leaves from pixel values of the image. The histogram of pixel values after gamma correction was converted into a PPFD histogram. The histogram pattern depended on the light source and canopy structure. Histograms estimated from images could depict the differences, showing mean values and coefficients of variation (CV) close to the measured values. Integrated PPFD over all illuminated leaves per unit power consumption (IPPC) was calculated from the histogram as a criterion for evaluating the efficiency of supplemental lighting. The efficiency also depended on the light source, canopy structure, and distance from the canopy surface. The estimated efficiency approximately agreed with the measured value in each case. These results suggest that reflection-image-based estimation of light intensity distribution can be used for simple evaluation of the efficiency of supplemental lighting.

Key words: Digital camera, LED, Light control, Reflection image, Tomato canopy.

1. Introduction

Light intensity on a plant canopy surface is one of the critical factors affecting productivity in protected cultivation. Natural light levels often limit crop production (Hemming, 2011). Supplemental lighting with artificial lights is an effective way to control the light environment in a greenhouse. Supplemental lighting can be used to promote photosynthesis (*e.g.*, Hoshi *et al.*, 2011; Oh *et al.*, 2010), control the photoperiod for flowering (*e.g.*, Runkle *et al.*, 2011), and control morphogenesis (*e.g.*, Yamazaki *et al.*, 2011). In addition, recent advances in light-emitting diodes (LED) that can emit narrow-band wavelengths have made it possible to provide supplemental lighting at specific wavelengths. It has been reported that lighting at a specific wavelength could suppress plant disease (Kudo *et al.*, 2011; Tokuno *et al.*, 2012) and improve the quality of crops, for example, by increasing the amount of antioxidant content (Samuolienė *et al.*, 2012).

Although the importance of supplemental lighting has been increasing, very little attention has been paid to the efficiency of the lighting. As supplemental lighting consumes energy and leads to an increase in the cost of crop production, improving efficiency is important. Therefore, it is also important to develop a method to evaluate efficiency. As the direct objective of supplemental lighting is to increase light intensity on leaves, it is important to know to what extent the supplemental lighting can improve the light intensity.

Light intensity on a leaf surface can be evaluated as photosynthetic photon flux density (PPFD) or irradiance. PPFD is used to evaluate photosynthetic status and can be measured by a quantum sensor. However, determining the PPFD distribution on the canopy surface is difficult even with the sensor because of large

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variations in leaf angle/orientation in the plant canopy (Ibaraki *et al*., 2012b). Thus, simple methods for estimating the light intensity distribution on the canopy surface are required.

Recently, it has been reported that diffuse reflection images of a plant canopy at a specific wavelength could be used for estimation of light intensity on leaves (Ibaraki *et al*., 2012b). The use of images acquired from different directions could minimize the effect of specular reflection, and high correlations between PPFD and average pixel values in the reflection images were observed. Based on this knowledge, a method to estimate light intensity distribution using reflection images has been developed (Ibaraki *et al*., 2012b). In this method, the reflection images were acquired from three different directions, and PPFD on leaves was estimated from the averaged pixel values of the reflection images using a linear relationship between pixel values and PPFD although estimation of PPFD distribution on a canopy surface was effective only for canopies consisting of homogenous leaves (in color and texture). Moreover, a PPFD histogram of a tomato canopy under sunlight could be constructed using this method (Ibaraki *et al*., 2012a).

In the current study, to develop a way to evaluate the efficiency of supplemental lighting, criteria for efficiency based on PPFD distribution on the canopy surface under artificial lighting have been proposed, and the possibility of reflection-image-based estimation of PPFD distribution on the canopy surface is discussed.

2. Materials and Methods

2.1 Plant materials and acquisition of reflection images of the plant canopy

Tomato plants (*Solanum lycopersicum* L., 'Momotaro') germinated on rockwool cubes (MU 60/60, Grodan) in a greenhouse were used as plant materials.

Reflection images of the tomato plant canopy were acquired from three different directions using a digital camera (SX110, Canon) equipped with a blue-green band-pass filter (S76-BG7, Suruga). The filter had a peak wavelength of 480 nm and was chosen based on the results of a preliminary experiment that tested several optical filters (Ibaraki *et al*., 2012b). To acquire an image from three different directions, the cameras were moved horizontally at intervals of 20-45 degrees at a fixed distance (50 cm) from the canopy surface. The imaging field of view from a distance of 50 cm was 70 cm × 50 cm, and in this configuration, the resolution of the images was 0.78 mm per pixel. In the imaging configuration used in this study, about 100 leaflets could be imaged at a time, although this depended on the type of canopy.

The RGB color images were converted into grayscale images based on the brightness using image-processing software (PHOTOSHOP 6.0, Adobe). Pixel values were gamma-corrected using a predetermined gamma value of 0.7 for the digital camera.

2.2 Lighting devices for supplemental lighting

A portable fluorescent work light fixed on a flexible arm, a white LED light, and a violet LED light were used for supplemental lighting. The fluorescent light was equipped with a 12 W three-wave day-white fluorescent lamp (EFD15EN/12, Ohm) and the lighting angle was changeable. The white LED light consisted of 8 LED units mounted with 12 white LED lamps (NSPW500D, Nichia) whose emitting angle was 15°. The violet LED light consisted of 9 LED units with 12 LED lamps (SL405AAUE, Sunopto) with a peak wavelength of 405 nm and an emitting angle of 15°. The arrangement of the LED units was flexible and the distance between the LED units was changeable. In this study, the LED units were set in a line. The intensity of the light could be varied by changing the level of the electric current in both the white and the violet LED lights.

To understand the light intensity of the illumination from each light source and evaluate the efficiency of the lighting, a portion of the tomato plant canopy was illuminated by each lighting device at night without using any other artificial light.

2.3 Confirmation of linearity of pixel values and PPFD on the leaf surface under each light source

The relationship between pixel values and PPFD on the leaf surface was investigated to examine the possibility of estimating a PPFD histogram from reflection images under each supplemental lighting device. PPFD on the leaf surface was measured with a quantum sensor (LI-190A, Li-cor) after imaging. The quantum sensor was set just behind the target leaf, and PPFD was measured when the leaf was gently displaced by hand. The measurements were performed for 10 leaves located on the surface of the canopy consisting of tomato seedlings with 5 compound leaves when the canopy was illuminated by each light source.

The gamma-corrected pixel value in the area corresponding to the measurement point in each reflection image was averaged for the images from the three directions. The relationship between PPFD on a leaf and the pixel value of the corresponding area in the reflection image was analyzed.

2.4 Comparison between estimated and measured PPFD histograms（Exp. 1）

In Exp.1, tomato plant canopies cultivated in a greenhouse and canopies of tomato seedlings in an experimental room were illuminated by two different lighting devices（the white LED and the fluorescent lamp）. The PPFD distribution on the canopy surface was determined using the quantum sensor or reflection images and the results were compared.

A tomato canopy grown on rockwool mats（GROTOP, Grodan）at intervals of 32 cm in a plastic greenhouse at Yamaguchi University（Yamaguchi, Japan）was used. The canopy, which consisted of tomato plants of 120 cm in height with 18 compound leaves, was illuminated from the side by the lighting devices. In the experiment conducted in the experimental room, 10 tomato seedlings with 3-5 compound leaves were set in a plastic tray（650×320 mm）to form a canopy. The lighting devices were set obliquely up towards the canopy in the experimental room. The lighting conditions including the distance from the canopy surface and the power consumption are listed in Table 1.

To construct the PPFD histogram, PPFD was measured at one point on the canopy using the quantum sensor simultaneously with imaging, and the result was used to determine a regression model（a linear model）to estimate PPFD on the leaves from the image pixel values. The quantum sensor was set just next to the leaf at the same inclination as the leaf, and PPFD was recorded simultaneously with imaging.

Figure 1 is a flow diagram of the construction of the PPFD histogram. Pixels corresponding to the plant canopy in the images were extracted by manual inspection using the image-processing software, and the images were then converted into gray-scale images. A PPFD histogram was constructed in the following way. First, a histogram of pixel values before gamma-correction was obtained. Next, each class mark（pixel value）was gamma-corrected and then converted to a PPFD value using the linear model. The number of pixels for each PPFD mark was reconstructed according to the interval of the PPFD histogram（0.5 μmol m^{-2} s^{-1} or 1 μmol m^{-2} s^{-1}）. Areas in which estimated PPFD was lower than 0.4 μmol m^{-2} s^{-1} were eliminated from the analysis.

After imaging, PPFD was measured for all leaves in the imaging field in the manner described in Section 2.3, and a PPFD histogram was obtained based on the actual measurements. The number of leaflets for which PPFD was actually measured was 53-82 and 112-123 for the canopy in the greenhouse and in the experimental room, respectively.

Histograms obtained from actual measurements and estimated from reflection images were used to calculate the efficiency of lighting.

2.5 Efficiency of lighting under different lighting conditions with violet LED light（Exp. 2）

Experiment 2 attempted to determine the optimal position of the lighting device based on the lighting efficiency estimated from reflection images. Three tomato plants of 40 cm in height with 10 compound leaves were set in a line at intervals of 15 cm and were

Table 1. Lighting efficiencies measured and estimated from reflection images under various lighting conditions（Exp. 1）.

Light source	Canopy	Distance（cm）	IPPC（μmol s^{-1} W^{-1}）		Projected area（m^2）	Power Consumption（W）
			Measured	Estimated		
Fluorescent lamp	Room	30	0.061	0.071	0.12	10.2
	Room	40	0.091	0.092	0.16	10.2
	Greenhouse	30	0.071	0.064	0.15	10.2
LED lamp	Room	30	0.094	0.095	0.09	7.7
	Room	40	0.074	0.082	0.08	4.8
	Greenhouse	30	0.14	0.14	0.20	4.8

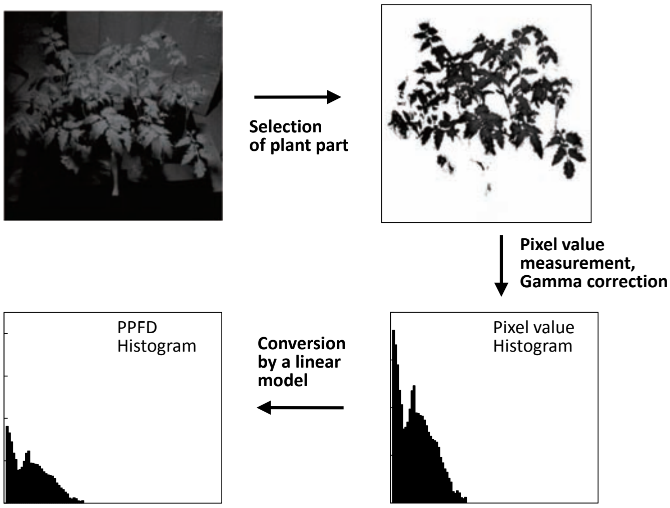

Fig. 1. Flow diagram of PPFD histogram construction from reflection images.

illuminated by the violet LED light consisting of 9 violet LED units. The LED light was set directly or diagonally (left or right) from the front of the largest compound of the center plant.

For the light directly in front of the center plant, three distances (5, 10, and 15 cm) from the canopy surface were tested; the lights placed diagonally were tested at a distance of 5 cm (Fig. 2). Reflection images of tomato plant canopies were acquired in a manner similar to that described in Section 2.1. PPFD was measured simultaneously with imaging at one point on the canopy by the quantum sensor set just next to the leaf at the same inclination as the leaf. A PPFD histogram was obtained from the reflection images in a manner similar to that described in Section 2.4. The efficiency of the supplemental lighting was calculated for each lighting condition.

2.6 Evaluation of efficiency of supplemental lighting

To characterize the PPFD distribution under various lighting conditions, averaged PPFD over the illuminated canopy surface and the coefficient of variation (CV) of PPFD were calculated from the PPFD histogram. Integrated PPFD over all illuminated leaves per unit power consumption (IPPC) was then calculated as a criterion for evaluating the efficiency of supplemental lighting. IPPC was calculated by the following equation:

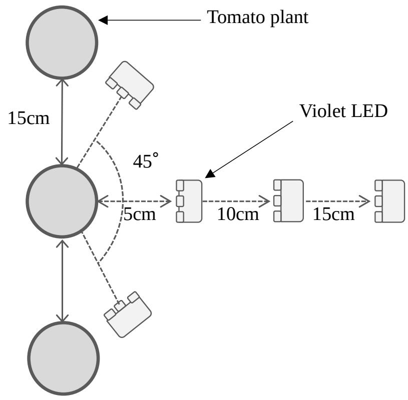

Fig. 2. Schematic layout of supplemental lighting with violet LED light (Exp.2) (Top view).

$$\mathrm{IPPC}\left(\mu\mathrm{mol\,s^{-1}\,W^{-1}}\right) = \frac{\text{Averaged PPFD}\left(\mu\mathrm{mol\,m^{-2}\ s^{-1}}\right)\times \text{Projected leaf area}\left(\mathrm{m^{2}}\right)}{\text{Power consumption of light source}\left(\mathrm{W}\right)} \tag{1}$$

The projected leaf area was estimated from the image of the canopy surface by selecting pixels corresponding to leaves by manual inspection.

3. Results and Discussion

3.1 Relationship between pixel values and PPFD under each light source

The pixel values in the reflection images of the tomato canopy increased with PPFD measured using the quantum sensor on the target leaf. A strong linear correlation between PPFD on leaves and the gamma-corrected pixel values of the corresponding area in the reflection images was obtained for all lighting devices tested (R^2=0.99 for the fluorescent light, R^2=0.98 for the white LED light, and R^2=0.98 for the violet LED light) (Fig. 3). This suggests that PPFD on a leaf surface illuminated with each lighting device can be estimated using a linear model from the pixel value in the reflection images acquired with the digital camera. The possibility of image-based estimation of PPFD distribution has also been shown for plant material in a greenhouse under natural sunlight (Ibaraki *et al.*, 2012a). The image-based estimation method of PPFD on a leaf is expected to be used under various light environments. However, it should be noted that the linear regression model depends on the light source and the properties of the canopy, including species and leaf status. Therefore, the model should be determined based on PPFD measured at one point in each imaging.

3.2 Comparison between estimated and measured PPFD histograms and efficiencies of lighting (Exp. 1)

Figure 4 shows the histograms estimated from the reflection images and observations (actual measure-

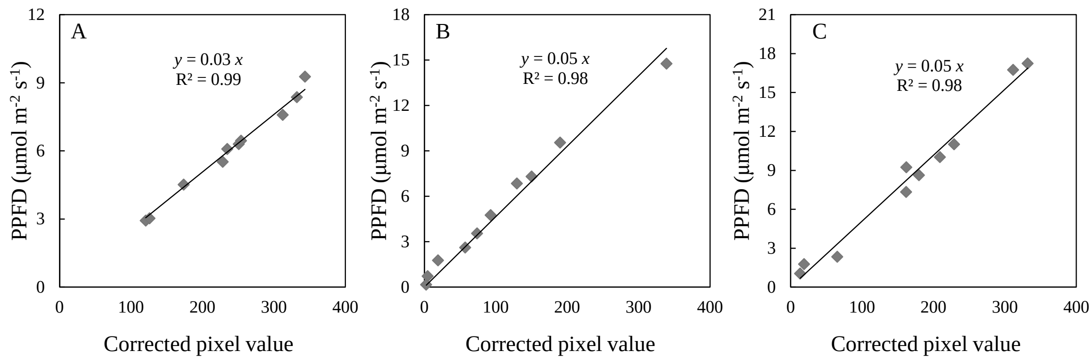

Fig. 3. Relationship between PPFD on leaves and average pixel values in reflection images from three directions for fluorescent light (A), white LED light (B), and violet LED light (C).

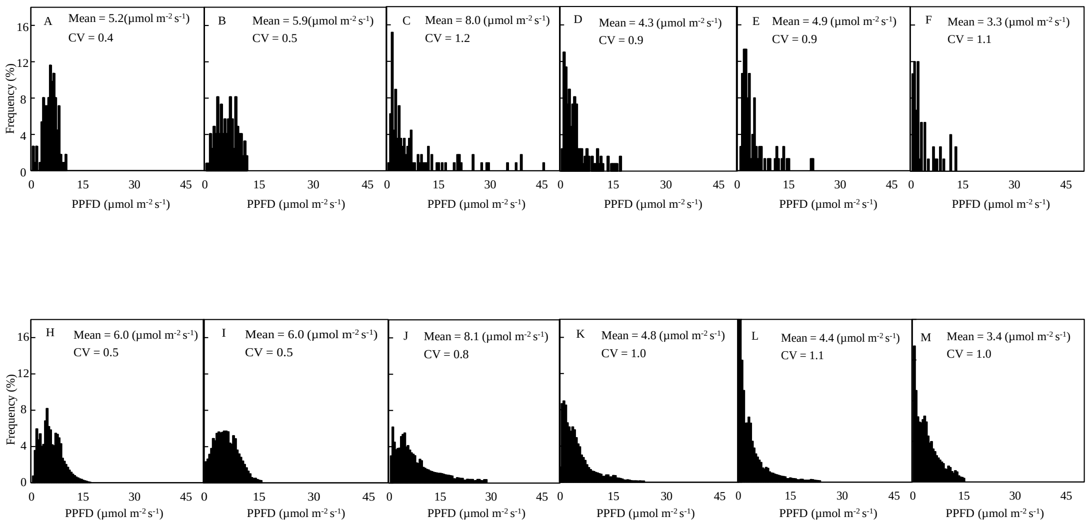

Fig. 4. Histograms of PPFD measured (A-F) and estimated from reflection images (H-M) under various lighting conditions (Exp. 1). Fluorescent light 40 cm (A, H), 30 cm (B, I), the white LED 30 cm (C, J), 40 cm (D, K) in the experimental room, and fluorescent light (E, L) and the white LED (F, M) in the greenhouse (30 cm).

ments) for two canopy types (in the greenhouse and in the experimental room), and two lighting devices. The histogram pattern depended on the light source and canopy structure. The fluorescent light tended to show a bell-shaped histogram, while the white LED light showed a histogram with a long tail to the right.

Histograms estimated from the images could depict the differences, showing mean values and CVs close to the measured values. However, the pattern of the estimated histograms was smoother than that of the measured histograms. PPFD was measured at one point, or a few points at most, for each leaf in order to construct a histogram based on actual measurements, even though there was variation in PPFD within a single leaf. The histogram estimated from reflection images was expected to reproduce the distribution within a leaf (Ibaraki *et al*., 2012a).

Table 1 shows the efficiency of supplemental fluorescent and LED lighting (IPPC) under various conditions. The efficiency also depended on the lighting device, canopy structure, and lighting condition. The IPPC of the white LED was higher on the canopy in the greenhouse than in the experimental room. In the canopy in the greenhouse, the tomato leaves were larger compared with those in the canopy in the experimental room, and light from the LED with a narrow emitting angle was therefore intercepted efficiently by the leaves. The effects of the lighting distance depended on the lighting device.

The efficiency estimated from the images agreed with the measured value in each case, reproducing the differences among lighting devices or canopy types (Fig. 5). The result shows that an image-based estimation method of PPFD distribution on canopy surfaces could be used to evaluate lighting efficiency under artificial light.

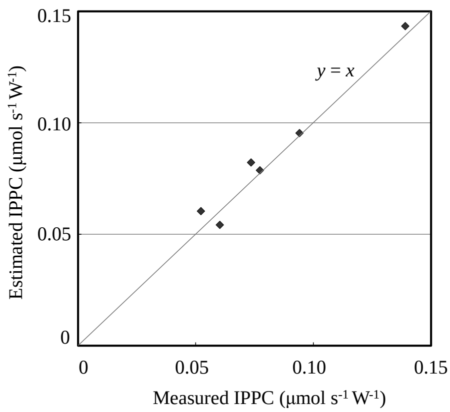

Fig. 5. Relationship between IPPCs calculated from PPFD histograms measured and estimated.

3.3 Efficiency of lighting under different lighting conditions with violet LED light (Exp. 2)

Figure 6 shows the PPFD histograms under various conditions using the violet LED lighting device consisting of 9 LED units. The distribution pattern of PPFD depends on the distance from the lighting device and lighting direction, and, as a result, the efficiency of lighting changed (Table 2). Under the conditions of this experiment, IPPC was increased when the lights were close to the canopy surface due to an increase in both averaged PPFD and projected area. Although lights placed at a relatively long distance from the plants expand the area illuminated, light intensity was decreased, especially in the area that deviated from the optical axis of the LED lamps. In this study, areas with less than 0.4 μmol m^{-2} s^{-1} were excluded from analysis, and as a result, the projected area was decreased for the longer distance (15 cm). Moreover, at a distance of 5 cm, histogram patterns and IPPC changed with the imaging direction because the tomato leaves were rela-

Table 2. Lighting efficiencies estimated from reflection images under various lighting conditions with violet LED light (Exp. 2).

Distance (cm)	Direction	IPPC (μmol s^{-1} W^{-1})	Projected area (m^2)	Power consumption (W)
5	Front	0.068	0.019	6.3
10	Front	0.043	0.016	6.3
15	Front	0.038	0.015	6.3
5	Diagonally right	0.038	0.011	6.3
5	Diagonally left	0.056	0.015	6.3

tively regularly distributed and, consequently, the portion of light intercepted by leaves depended on the direction of lighting.

From the viewpoint of IPPC, the most effective lighting condition tested in this experiment was illumination from the front of a plant at a distance of 5 cm. However, it should be noted that variations（CVs）, which should be taken into consideration when evaluating PPFD distribution, increased with a decrease in the distance（Fig. 6）. Large variations in PPFD might cause variations in the effects of supplemental lighting. Therefore, less variation in PPFD is desired. However, the importance of homogeneity in light intensity distribution has not been well studied because there was no way to evaluate it properly and simply. The image-based PPFD histogram estimation method is expected to be used for this purpose.

It has been reported that supplemental violet LED lighting with a peak wavelength of 405 nm had the effect of suppressing tomato plant disease（Tokuno *et al.*, 2012）. In the experiment, the LED lights were set so that irradiance at the nearest leaf was 30 W m^{-2}, which corresponds to approximately 75 μmol m^{-2} s^{-1}. At a distance of 15 cm, the maximum PPFD on the canopy surface was 60 μmol m^{-2} s^{-1}, and this requirement was not stratified. At 5 cm, the area in which PPFD was more than 75 μmol m^{-2} s^{-1} was approximately 6％ of the total area. However, the ratio changed for light sources from different directions at the same distance. Optimal positioning of the light might depend on the leaf distribution pattern in a canopy, especially in the case of small lighting devices. The leaf distribution pattern in a canopy changes with plant growth, and the position of supplemental lighting might therefore need to be changed with growth. The PPFD histogram estimation method can also be used to check PPFD distribution for determining optimal positioning during cultivation.

When artificial lights are used, it is easy to convert PPFD into total photon flux density（PFD）or irradiance（Wm^{-2}）because, for the same light source, the light spectrum is constant. Therefore, the developed method can be applied for supplemental lighting that should be evaluated by PFD or irradiance rather than PPFD.

The supplemental light sources used in this study were small, low-power devices（4.8-10.2 W）because obtaining actual PPFD distributions by manual meas-

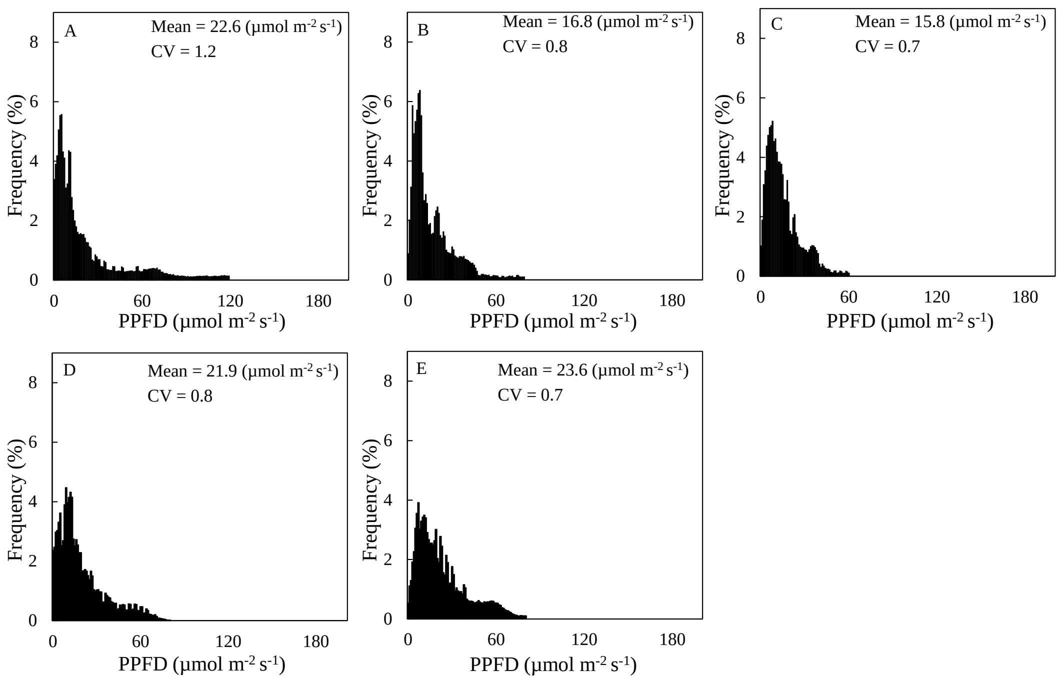

Fig. 6. Histograms of PPFD estimated from reflection images under various lighting conditions with violet LED light（Exp. 2）. Front 5 cm（A）, 10 cm（B）, 15 cm（C）, right（D）and left（E）.

urement with a PPFD sensor would be difficult for large, high-power light sources that can illuminate a larger area. The averaged PPFDs obtained from the experiments conducted were small and not necessarily applicable if supplemental lighting is intended to enhance photosynthesis. However, the obtained results suggest that the method could be applied to large lighting devices with high power consumption and high-intensity PPFD distribution. The use of a wider-angle lens is expected to enable us to investigate a larger area at a time (Ibaraki *et al*., 2012b).

In this study, IPPC was proposed as the criterion for evaluating the efficiency of supplemental lighting. Other than average values, the statistics also include median and mode values for PPFD distribution. These statistical values can be calculated from the PPFD histograms obtained using reflection images. Further research to investigate the relationships between PPFD distribution and plant growth is necessary in order to determine which statistical values should be used to evaluate lighting efficiency.

4. Conclusions

To develop a simple and useful method for evaluating the efficiency of supplemental lighting based on PPFD distribution on the canopy surface, PPFD histograms for the canopy surface under artificial lighting were constructed from reflection images. These PPFD histograms showed a pattern similar to that of the PPFD histograms constructed from the measured PPFD distributions. Integrated PPFD over all illuminated leaves per unit power consumption could be calculated from the PPFD histograms as the criterion for the efficiency of the lighting. The estimated efficiency approximately agreed with the measured value in each case. These results suggest that reflection-image-based estimation of light intensity distribution is a simple method that can be used to evaluate the efficiency of supplemental lighting. This method can be applied to help optimize supplemental lighting conditions.

Moreover, it is important to know the actual light intensity of the artificial light irradiating the plant canopy surface so as to improve stability and repeatability in environmental control where supplemental lighting is used. The image-based PPFD histogram estimation method is also expected to be used for this purpose.

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References

Hemming, S., 2011: Use of natural and artificial light in horticulture—Interaction of plant and technology. *Acta Hortic*., **907**, 25−35.

Hoshi, T., Higa, H., Goto, K., and Niibori, K., 2011: Effects of supplemental lighting on the quality of tomato seedlings raised in greenhouses. *Acta Hortic*., **907**, 117−124.

Ibaraki, Y., Kishida, T., and Shigemoto, C., 2012a: Image-based estimation of PPFD distribution on the canopy surface in a Greenhouse. *Acta Hortic*., **956**, 577−582.

Ibaraki, Y., Yano, Y., Okuhara, H., and Tazuru, M., 2012b: Estimation of light intensity distribution on a canopy surface from reflection images. *Environ*. *Control Biol*., **50**, 117−126.

Kudo, R., Ishida, Y., and Yamamoto, K., 2011: Effects of green light irradiation on induction of disease resistance in plants. *Acta Hortic*., **907**, 251−254.

Oh, W., Runkle, E. S., and Warner, R. M., 2010: Timing and duration of supplemental lighting during the seedling stage influence quality and flowering in petunia and pansy. *Hortic. Sci*., **45**, 1332−1337.

Runkle, E. S., Padhye, S. R., Blanchard, M. G., and Oh, W., 2011: Energy-efficient greenhouse lighting of ornamentals. *Acta Hortic*., **907**, 53−60.

Samuolienė, G., Sirtautas, R., Brazaitytė, A., and Duchovskis, P., 2012: LED lighting and seasonality effects antioxidant properties of baby leaf lettuce. *Food Chem*., **134**, 1494−1499.

Tokuno, A., Ibaraki, Y., Ito, S., Araki, H., Yoshimura, K., and Osaki, K., 2012: Disease suppression in greenhouse tomato by supplementary lighting with 405 nm LED. *Environ*. *Control Biol*., **50**, 19−29.

Yamazaki, K., Kumakura, H., and Hamamoto, H., 2011: Effect of light quality for supplemental lighting during runner-cooling treatment on flowering of strawberry in forcing culture. *Acta Hortic*., **907**, 291−294.