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Measurement System of Photosynthetic Photon Flux Distribution and Illumination Efficiency of LED Lamps for Plant Growth

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Abstract

Purpose: This study was conducted to develop a measurement system for determining photosynthetic photon flux (PPF) distribution and illumination efficiency of LED lamps. **Methods:** The system was composed of a linear moving sensor part (LMSP), a rotating part to turn the LMSP, a body assembly to support the rotating part, and a motor controller. The average PPF of the LED lamp with natural cooling and water cooling was evaluated using the measurement system. **Results:** The PPF of LED lamp with water cooling was 3.1-31.7% greater than that with natural cooling. Based on the measured value, PPF on the horizontal surface was predicted. Illumination efficiency of the LED lamp was slightly increased with water cooling by 3.4%, compared with natural cooling. A simulation program using MATLAB was developed to analyze the effects of the vertical distance from lighting sources to growing bed, lamp spacing, and number of LED lamps, on the PPF distribution on the horizontal surface. The uniformity of the PPF distribution of the LED lamps was fairly improved with 15 cm spacing, as compared to the 5 cm spacing. By simulation, PPF of 217.0±27.9 $\mu mol \cdot m^{-2} \cdot s^{-1}$ was obtained at the vertical distance of 40 cm from six LED lamps with 12 cm spacing. This simulated PPF was compared to the measured one of 225.9±25.6 $\mu mol \cdot m^{-2} \cdot s^{-1}$. After continuous lighting of 346 days, the relative PPF of LED lamps with water cooling and natural cooling was decreased by 6.6% and 22.8%, respectively. **Conclusions:** From these results, it was concluded that the measurement system developed in this study was useful for determining PPF and illumination efficiency of artificial lighting sources including LED lamp.

Keywords: Artificial lighting source, Illumination efficiency, LED, Photosynthetic photon flux

Introduction

Light is one of the most important environmental factors that govern plant growth, development, photosynthesis, photomorphogenesis, and photoperiodism (Chen et al., 2004; Spalding and Folta, 2005; Kami et al., 2010; Fankhauser and Chory, 1997). Light-emitting diodes (LED) lamps have been considered as new artificial lighting sources for plant growth due to their relatively small mass and volume, low electric consumption, long lifetime, specific wavelength, and easy pulse drive (Barta et al., 1992; Bula et al., 1991). Until now, LED lamps have been widely used as light sources to promote photosynthesis (Goins et al., 1997; Tennessen et al., 1995), to control photomorphogenic responses (Brown et al., 1995; Stutte, 2009), and to enhance phytochemicals (Wu et al., 2007; Li and Kubota, 2009). Some studies on the application of LED lamps to improve growth and the efficiency of light utilization in lettuce production (Lee et al., 2011), and to enhance seedling quality and growth after transplanting of some vegetables (Li and Kubota, 2009; Lee et al., 2010) were reported.

Advances in LED lamps with high power and high intensity would be of great interest to greenhouse growers because they could be used as supplemental lighting sources to promote growth and yield in horticultural

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crops. However, some LED lamps which were provided to growers were made by small-sized manufacturers. These small-sized manufacturers do not obtain the certificate of LED lamps, so the performances of the lamps such as lifetime, illumination efficiency, and peak spectral output including photosynthetic photon flux (PPF) were not verified. LED lamps generate heat which should be removed to ensure maximum performance and lifetime. Park et al. (2011) demonstrated that PPF illuminated from LED lamps was increased with water cooling system. However, the lifetime of the LED lamps could be decreased because of the excessive heat. Even though LED has many advantages over traditional lighting sources, it should be used carefully. Thus a total system approach must be considered for designing an LED-based lighting system (Bourget, 2008).

Recently, LED lamps have been tested for using new artificial lighting sources in protected horticulture or plant factory, however, there were no reports on their performances. In addition, the bar-type LED lamp is difficult to measure the illumination efficiency using integrating sphere. It is also difficult to measure the PPF distribution of LED lamps because the PPF distribution is affected by the number of installed lamps, lamp spacing, and the vertical distance between lamps and growing bed. The objective of this study is to develop a measurement system for determining PPF distribution and illumination efficiency of LED lamps which could be used as artificial lighting sources for plant growth.

Materials and Methods

The developed measurement system of PPF of LED lamps in a plant growth room (2,800×3,180×2,650 mm) was composed of a linear moving sensor part (LMSP), a rotating part to turn the LMSP, a body assembly (1,580×1,219×847 mm) to support the rotating part, and a motor controller (Fig. 1). LMSP can be horizontally slid by a step motor (KH42JM2-901, Servo, Japan) connected to the rotating part. A prototype motor controller was used to control the position of the step motor and a DC motor (S8D40-2490A, SPG, Korea) to adjust the rotation angle of the rotating part. A Bluetooth serial converter (Parani-SD100, SENA Technologies Inc., USA) was used for wireless communication between the motor controller and host computer.

The moving distance of LMSP was 0-1,100±1 mm and the degree of rotating part was 160±0.5°. A leveling instrument and a protractor were used for measuring the reference angle of the rotating part. The bar-type LED lamps (PlantLED V1.1, Oditech Ltd. Co., Korea) with the dimension of 4×120 cm were used for the analysis of the PPF distribution of artificial lighting source. The PPF distribution on every 5° angle and every 10 cm distance of the LMSP was measured using the quantum sensor (LI190S, LI-COR, USA) attached on the LMSP. Measured PPF was used to determine predicted PPF along the circular arc formed by movement of the rotating part. Cumulative PPF was calculated by integrating the predicted PPF at each angle along the LED length. Finally, illumination efficiency of the LED lamps was defined as the cumulative PPF divided by the electric power consumption and the area receiving the PPF illuminated from the LED lamps. MATLAB (2010b, The Mathworks, Inc., USA) was used to simulate the illumination efficiency of the LED lamps and to estimate the PPF distribution on the growing bed. Finally, comparison between the estimated PPF and the measured one was made.

A hall sensor (WCS1702, DIWELL Electronics Co., Korea) was used to measure the applied current flowing through the LED lamps. Based on the applied current, the electric power consumed by the LED lamps was obtained. After that, the illumination efficiencies of the LED lamps were obtained in two types of cooling methods: natural cooling and water cooling. A cooler (DA-100B, DAEIL, Korea) with a temperature regulator (DOV-882, DAEIL, Korea) was used to control the water temperature for cooling. Cold water was circulated from water tank through flex tube installed inside the aluminum plate to cool down the excessive heat of LED lamps. Temperature and flow rate of cold water were maintained at 23℃ and 1.5 L·min^{-1}, respectively.

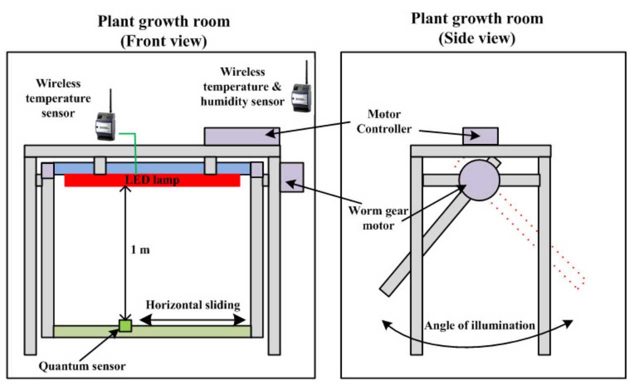

Figure 1. Diagram of the measuring system of photosynthetic photon flux distribution of LED lamps.

PPF, temperature, relative humidity, and electric current were measured using a data logger (CR23X, Campbell, USA). The measurements were performed in a plant growth room maintained at 24℃ air temperature and 70% relative humidity.

Results and Discussion

Fig. 2 shows the PPF of the LED lamp by angle of illumination and cooling method. In this experiment, PPF was measured at a distance of 50 cm from the LED lamp. The maximum PPF of LED lamp was found at the angle of 0° and the PPF was decreased with increasing angle of illumination. PPF of LED lamp with water cooling was increased and 3.1-31.7% greater than that with natural cooling. This result was due to the increased forward voltage of LED lamp as ambient temperature surrounding LED chips was lowered (Park et al., 2011).

As shown in Table 1, cumulative PPF of the LED lamps by cooling method was 396.1 mmol·s^{-1} for natural cooling and 427.9 mmol·s^{-1} for water cooling. Considering the electric power consumed by the LED lamps, the illumination efficiency of the LED lamps with different cooling method was calculated by 11.7 mmol·s^{-1}·W^{-1} for natural cooling and 12.1 mmol·s^{-1}·W^{-1} for water cooling. Thus illumination efficiency of the LED lamp was increased with water cooling by 3.4% (Table 1), compared with natural cooling.

A simulation program using MATLAB was built to predict the PPF distribution on horizontal surface (Fig. 3). Then the PPF distribution on horizontal surface was simulated according to the vertical distance from lighting sources to growing bed, lamp spacing, and the number of LED lamps. Fig. 4 shows the PPF distribution simulated at the distance of 40 cm from four LED lamps with different spacing. The uniformity of the PPF distribution was fairly improved with 15 cm spacing, as compared to the 5 cm spacing. By simulation, PPF of 217.0±27.9 μmol·m^{-2}·s^{-1} was available at a vertical distance of 40 cm from six LED lamps with a 12 cm spacing. This simulated PPF was compared to the measured one of 225.9±25.6 μmol·m^{-2}·s^{-1}. Difference in PPF between measured and simulated value was only 3.9% even though the simulated PPF was slightly lower than the measured one. Thus we recognized that the PPF measurement system developed in this study could be effectively used to predict the light intensity illuminated from any artificial lighting sources including LED lamps.

Light intensity illuminated from LED lamps is decreased with the time elapsed after starting of the lighting. Fig. 5 shows the variation of relative PPF, defined as the ratio of PPF measured at a specified time to initial PPF, as affected by elapsed time and cooling method. On 346th days (8,304 h) after continuous lighting, the relative PPF was

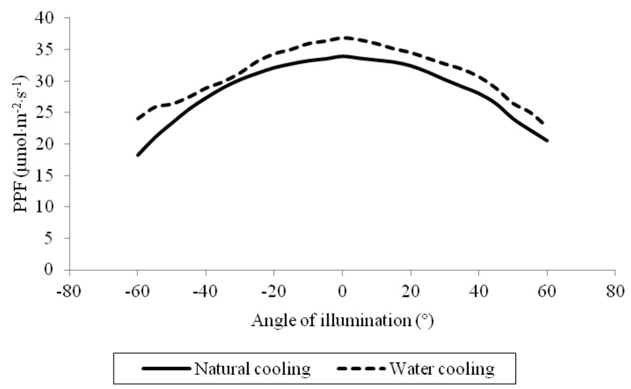

Figure 2. Measured photosynthetic photon flux (PPF) of the LED lamp by angle of illumination and cooling method.

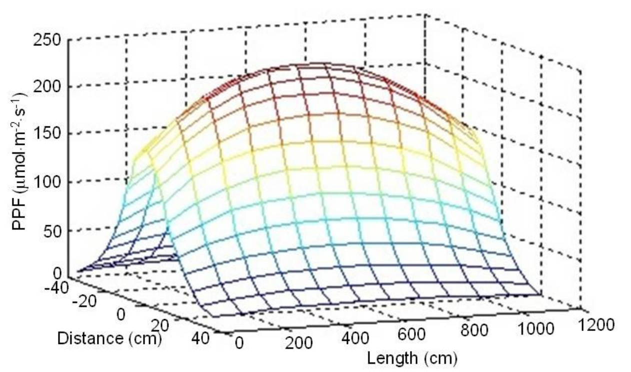

Figure 3. Predicted photosynthetic photon flux (PPF) distribution on horizontal surface at a vertical distance of 20 cm from LED lamp with natural cooling.

Table 1. Cumulative photosynthetic photon flux, electric power consumed, and illumination efficiency of the LED lamps by cooling method

Cooling method	Cumulative photosynthetic photon flux (mmol·s^{-1})	Electric power consumed (W)	Illumination efficiency (mmol·s^{-1}·W^{-1})
Natural cooling	396.1	33.7	11.7
Water cooling	427.9	35.3	12.1

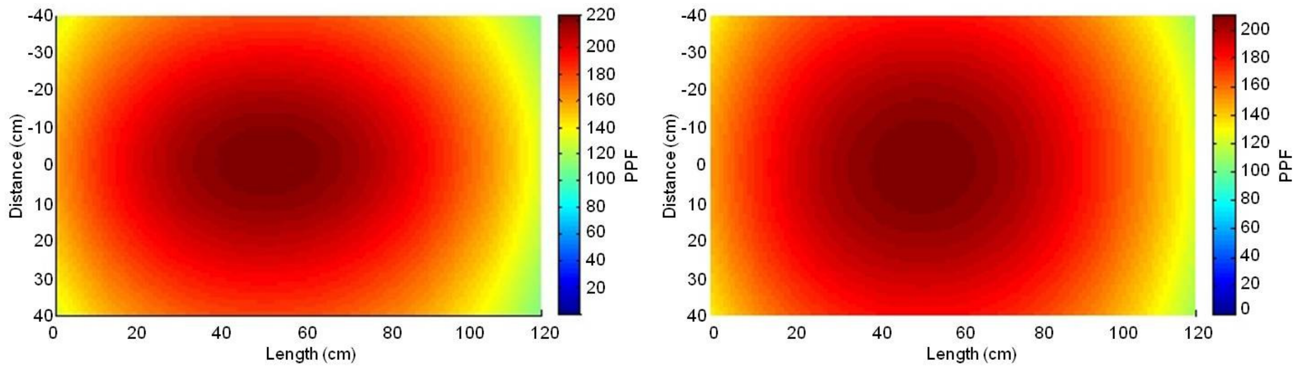

Figure 4. Comparison of simulated photosynthetic photon flux (PPF) distribution on horizontal surface at a vertical distance of 40 cm from four LED lamps with different spacing: (a) 5 cm spacing, (b) 15 cm spacing.

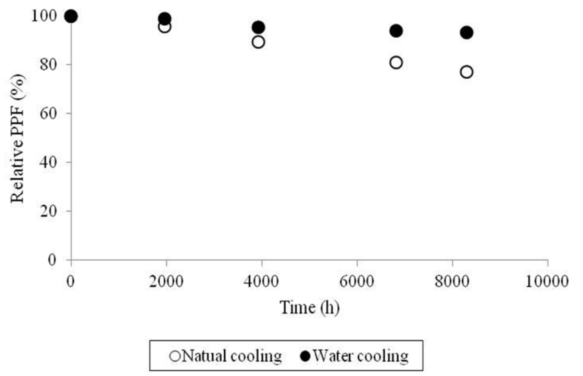

Figure 5. Ratio of photosynthetic photon flux (PPF) at a specified time to initial PPF as affected by time elapsed after continuous lighting and cooling method.

decreased with water cooling by 6.6%. It was compared to the natural cooling with reduction of 22.8%. Therefore, a proper cooling system should be required to dissipate the heat generated from LED chips effectively and to extend the lifetime of LED lamps. From these results, it was concluded that the measurement system developed in this study was greatly useful for evaluating PPF and illumination efficiency of artificial lighting sources including LED lamp. The developed measurement system would be used for designing the optimal lighting system and for improving the energy saving of artificial lighting sources for plant growth.

Conclusions

Recently, LED lamps have been tested for using new artificial lighting sources in protected horticulture or plant factory, however, there were no reports on the their performances. A measurement system to determine PPF and illumination efficiency of LED lamps was developed in this study. The average PPF of LED lamp according to the angle of illumination and cooling method was decided using the measurement system. PPF of LED lamp with water cooling was 3.1-31.7% greater than that with natural cooling. Based on the measured value, PPF on the horizontal surface was predicted. Illumination efficiency of LED lamp was increased with water cooling by 3.4%, compared with natural cooling.

A simulation program using MATLAB was developed to analyze the effects of the vertical distance from lighting sources to growing bed, to examine the effects of lamp spacing, and to explore the effects of the number of LED lamps on the PPF distribution on horizontal surface. By simulation, PPF of 217.0±27.9 $\mu mol \cdot m^{-2} \cdot s^{-1}$ was obtained at the vertical distance of 40 cm from six LED lamps with 12 cm spacing. It was compared to the measured PPF of 225.9±25.6 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Difference in PPF between measured and simulated value was only 3.9%. From these results, it was concluded that the measurement system developed in this study was greatly useful for determining PPF and illumination efficiency of artificial lighting sources including LED lamp. The developed measurement system would be used for designing the optimal lighting system and for improving the energy saving of artificial lighting sources for plant growth.

Conflict of Interest

The authors report no financial or other conflict of interest relevant to the subject of this article.

Acknowledgements

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References

Barta, D. J., T. W. Tibbitts, R. J. Bula and R. C. Morrow. 1992. Evaluation of light emitting diode characteristics for space-based plant irradiation source. Advances in Space Research 12(5):141-149.

Bourget, C. M. 2008. An introduction to light-emitting diodes. HortScience 43(7):1944-1946.

Brown, C. S., Schuerger, A. C. and Sager, J. C. 1995. Growth and photomorphogenesis of pepper plants under red light-emitting diodes with supplemental blue or far-red lighting. Journal of the American Society for Horticultural Science 120:808-813.

Bula, R. J., R. C. Morrow, T. W. Tibbitts, D. J. Barta, R. W. Ignatius and T. S. Martin. 1991. Light-emitting diodes as a radiation source for plants. HortScience 26(2): 203-205.

Chen, M., J. Chory and C. Fankhauser. 2004. Light signal transduction in higher plants. Annual Review of Genetics 38:87-117.

Fankhauser, C. and J. Chory. 1997. Light control of plant development. Annual Review of Cell and Developmental Biology 13:203-229.

Goins, G. D., N. C. Yorio, M. M. Sanwo and C. S. Brown. 1997. Photomorphogenesis, photosynthesis, and seed yield of wheat plants grown under red light-emitting diodes (LEDs) with and without supplemental blue lighting. Journal of Experimental Botany 48:1407-1413.

Kami, C., S. Lorrain, P. Hornitschek and. C. Fankhauser. 2010. Light-regulated plant growth and development. Current Topics in Developmental Biology 91:29-66.

Lee, H. I., J. S. Lee, J. H. Park and Y. H. Kim. 2011. Growth and light utilization efficiency of lettuce as affected by different artificial lighting sources and photoperiod. Proceedings of the Korean Society for Bio-environment Control 20(1):120-121. (In Korean)

Lee, J. S., H. I. Lee, J. H. Park and Y. H. Kim. 2010. Growth and yield after transplanting of sweet pepper seedlings nursed under artificial light. Proceedings of the Korean Society for Bio-environment Control 19(1):185-186. (In Korean)

Li, Q. and C. Kubota. 2009. Effects of supplemental light quality on growth and phytochemicals of baby leaf lettuce. Environmental and Experimental Botany 67(1): 59-64.

Park, C. H., J. S. Lee, D. E. Kim and Y. H. Kim. 2011. Analysis of optimum water cooling conditions and heat exchange of LED lamps for plant growth. Journal of Biosystems Engineering 36(5):334-341. (In Korean)

Spalding, E. P. and K. M. Folta. 2005. Illuminating topics in plant photobiology. Plant, Cell & Environment 28(1): 39-53.

Stutte, G. W. 2009. Light-emitting diodes for manipulating the phytochrome apparatus. HortScience 44(2):231-234.

Tennessen, D. J., R. J. Bula and T. D. Sharkey. 1995. Efficiency of photosynthesis in continuous and pulsed light emitting diode irradiation. Photosynthesis Research 44:261-269.

Wu, M. C., C. Y. Hou, C. M. Jiang, Y. T. Wang, C. Y. Wang, H. H. Chen and H. M. Chang. 2007. A novel approach of LED light radiation improves the antioxidant activity of pea seedlings. Food Chemistry 101:1753-1758.