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Characteristics of Low–light LED as Supplemental Lighting and Its Effects on Leaf Gas Exchange in Strawberry

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The aim of this study was to analyze the fundamental lighting characteristics (spectrum distribution and light intensity) of a low–light LED unit and its effect on gas exchange in strawberry leaves. This unit was newly developed to provide low–cost supplemental lighting for greenhouses. The low–light LED unit was made using 24 LED module chips, each of which were 1 m in length and 43.2 W. The electricity consumption of this unit was only 55% of that of the high–light LED previously reported by Hidaka *et al.* (2013). The spectrum characteristics of low–light LED were measured using a portable spectro–radiometer. The photosynthetic photon flux density (PPFD) was measured using a photon sensor, and its distribution was measured at five different heights from a reference plane (110 cm × 150 cm). Gas exchange in strawberry leaves under low–light LED (Low LED treatment) supplemental lighting and no lighting (Control treatment) were measured using a leaf chamber system. The results demonstrated that the spectrum distribution patterns of the low–light LED and the high–light LED were similar; we found that the relative light intensity of both LEDs peaked once near a wavelength of 450 nm and again near a wavelength of 550 nm. The PPFD and its horizontal distribution showed that, as the height of the light source increased, the PPFD and lighting regions decreased and increased, respectively. On the other hand, as the height of 20 cm, PPFD under supplemental lighting with the low–light LED increased by 2.1 times than natural condition. As a result, stomatal conductance and transpiration rate increased by 1.5 times and 1.2 times, respectively; further photosynthetic rate increased by 2.2 times. Thus, the low–light LED was demonstrated to have suitable wavelength for crop production. Furthermore, applying supplemental lighting with the low–light LED significantly improved light intensity and accelerated photosynthesis in strawberry.

Key words: light–photosynthesis, leaf gas exchange, energy saving, strawberry

INTRODUCTION

Light is one of the most important environmental elements in crop production (Jones, 2014). In Japan, crops often cannot receive suitable light intensity in the winter because of decreased solar radiation, and this should become a limiting factor in greenhouses. Consequently, the decrease in yield and quality are unavoidable in many crops. To address this problem, the use of supplemental lighting in greenhouses is continuously increasing. The previous study examined supplemental lighting (LED lamps and fluorescent lamps) to find the most effective lighting for strawberry production in greenhouses, concluding that LEDs were most efficient for strawberry growth and yield (Hidaka *et al.*, 2013).

The application of LED lighting systems in greenhouses has been widely used over the last two decades (Olle and Virsile, 2013). However, the use of LED lighting systems is usually impractical because of the high cost. This is a major reason why LED lighting cannot be used as the only source of supplemental lighting. Therefore, the development of a lighting system with lower initial and running costs is needed to obtain effective and inexpensive supplemental lighting for strawberry cultivation.

In this study, we developed a supplemental lighting unit using LED modules with relatively low initial costs and low intensity (i.e. low–light LED). We analyzed fundamental lighting characteristics (spectrum distribution and light intensity) of the low–light LED and its effect on leaf gas exchange (photosynthetic rate, transpiration rate, stomatal conductance) in strawberry plants.

MATERIALS AND METHODS

Supplemental lighting system

We used LED modules (AE–LED lamp 7X6, Akizuki Denshi Tsusho, Co., Ltd., Japan) to construct the low–light LED unit for supplemental lighting. Each module was 40 mm × 30 mm and 1.8 W. The low–light LED unit consisted of 24 modules, each measuring 1 m × 4 cm (Fig. 1). Thus, the low–light LED unit was a total of 43.2 W. The electrical consumption of our low–light LED

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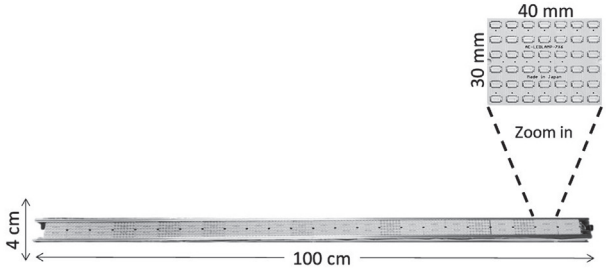

Fig. 1. Photograph of a low–light LED unit consisting of 24 LED module chips (AE–LED lamp 7X6, Akizuki Denshi Tsusho, Co., Ltd., Japan).

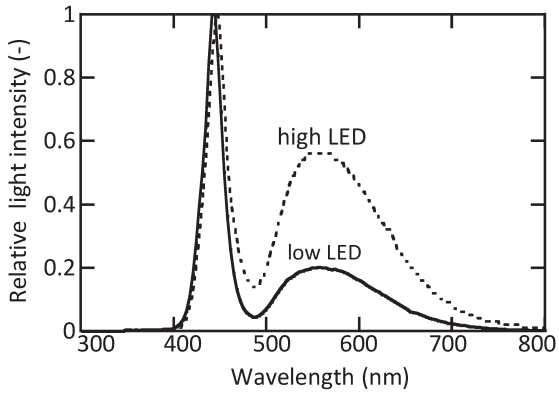

Fig. 2. Spectrum distribution of radiation emitted from the low–light LED. The data for the high–light LED are also shown (Hidaka *et al.*, 2013).

unit was only 55% of that of the high–light LEDs Hidaka *et al.* (2013) used.

Spectrum characteristics measurement

Spectrum characteristics were analyzed in the laboratory under dark conditions to avoid the contamination of natural light. Spectrum characteristics were measured using a portable spectroradiometer (MS–720, EKO Instrument Co., Ltd., Japan) at 10 cm under the low–light LED lighting system.

Light intensity and its spatial distribution measurements

We set one of the low–light LEDs above a reference plane (110 × 150 cm) where a 10 cm × 10 cm grid was made. The PPFD was measured at all grid points using a photon sensor (CAP – SQ – 110, Apogee) combined with a data logger (GL200A, Graphtec Co., Ltd., Japan). The height of the low–light LED was adjusted to five different levels: 10, 20, 30, 40, and 50 cm from the plane. The resulting PPFD measurements were drawn using a graphical software (Surfer ver. 11, Golden Software, Inc., USA).

Plant material and leaf gas exchange measurement

Strawberry plants (*Fragaria* × *ananassa* Duch. 'Fukuoka S6') grown in plastic pots (2.5 L) were used for leaf gas exchange measurements. We prepared two treatments on March 8, 2017: one included plants under the low–light LED supplemental lighting (Low LED treatment), and the other included plants with no supplemental lighting (Control treatment). PPFD on the 3rd leaf of each plant was measured using a quantum sensor coupled with a light meter (LI–250, Li–Cor, Inc. USA). Leaf gas exchange characteristics of stomatal conductance (*Gs*), transpiration rate (*Tr*), and photosynthetic rate (*A*) were then measured using a leaf chamber system (LI–6400XT, Li–Cor, Inc. USA) under the following conditions: air temperature of 25°C, relative humidity of 50%, and CO_2 concentration of 400 μmol mol^{-1}. Measurements were recorded for six leaves per treatment, and the data were statistically analyzed using a *t*–test.

RESULTS AND DISCUSSION

Lighting characteristics of the Low–light LED

Figure 2 depicts the spectrum distributions of our low–light LED (solid line) and the high–light LED (dashed line) previously reported by Hidaka *et al.* (2013; 2014); maximum light intensity was regarded as 1.0 for the respective LEDs. The distribution patterns were similar for both low– and high–light LEDs. Both low– and high–light LEDs shared two peaks near wavelengths of 450 nm and 550 nm. The maximum peak in both LEDs occurred near a wavelength of 450 nm, while the different peak proportion was found in the longer wavelength of 550 nm.

These results show that the low–light LED has a blue light spectrum that can induce stomatal opening (Doi *et al.*, 2015), as well as a low–intensity red light spectrum that can promote flowering and sugar accumulation (Shimazaki *et al.*, 2007). Although the stomatal response to blue light is greater than that of red light (Gorton *et al.*, 1993), the combination of lighting that contains blue light with a background of red light would cause additional stomatal opening (Ogawa *et al.*, 1978; Shimazaki *et al.*, 2007). Therefore, based on these results, the light quality of the low–light LED is appropriate as supplemental lighting for crops because it emits radiation in

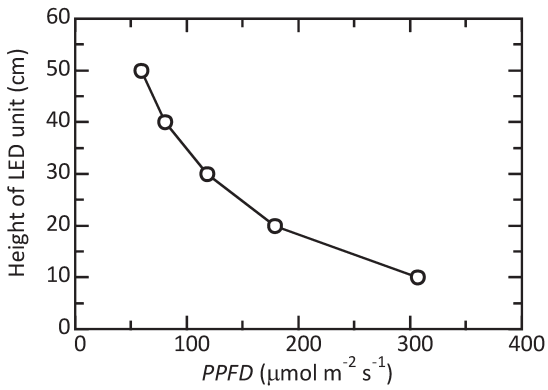

Fig. 3. Relationship between the height of low–light LED unit and photosynthetic photon flux density (PPFD).

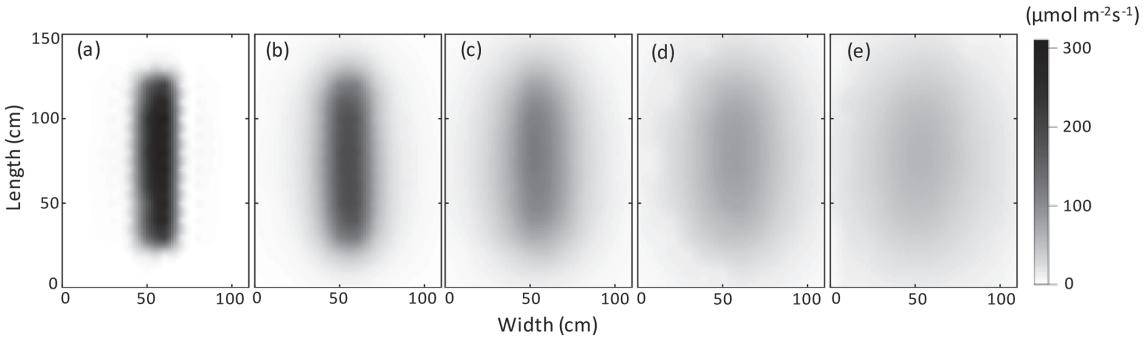

Fig. 4. Photosynthetic photon flux density (PPFD) distribution of the low–light LED in horizontal plane (110 × 150 cm) at different heights of 10 cm (a), 20 cm (b), 30 cm (c), 40 cm (d), and 50 cm (e).

certain wavelengths to the photosynthetically active radiation which lies between 400 nm – 700 nm (Jones, 2014).

Figures 3 and 4 show PPFD and its horizontal distribution at five varying heights, respectively. The maximum PPFD was found at 10 cm, while the largest illuminated region was observed at 50 cm. As the height of the light source increased, the light intensity and lighting regions decreased and increased, respectively.

Hidaka *et al.* (2013) reported that the photosynthetic rate in strawberry leaves rapidly increased under light intensity from 0–100 μmol m^{-2} s^{-1} and was near saturation when PPFD reached 400 μmol m^{-2} s^{-1}. Strawberry reproduction was also affected by light intensity (Darnell *et al.*, 2003), where reproductive biomass of *Fragaria vesca* (the Alpine strawberry) significantly increased under light intensity from 22 to 150 μmol m^{-2} s^{-1}. Therefore, we can expect the reasonable height of setting the low–light LED is approximately 20 cm from the top of crops which condition has suitable PPFD value around 180 μmol m^{-2} s^{-1} for supplemental lighting and adequate lighting regions for cultivated strawberry on the bench with large canopy of approximately 20–30 cm.

Effects of the Low–light LED on leaf gas exchange in strawberry

Figure 5 shows the PPFD, Gs, *Tr*, and *A* for the Low–light LED and Control treatments. Measured on a cloudy day, supplemental lighting in the Low LED treatment increased PPFD by 2.1 times (375 μmol m^{-2} s^{-1}) from that of the natural conditions in the Control treatment (178 μmol m^{-2} s^{-1}), where *A* was increased by 2.2 times. We concluded that increasing PPFD through the low–light LED supplemental lighting significantly promoted photosynthesis in strawberry leaves ($P < 0.001$). These results are consistent with those of Hidaka *et al.* (2013), who reported that increasing PPFD over 200 μmol m^{-2} s^{-1} through supplemental lighting gradually increased the rate of photosynthesis.

On the other hand, *G*s and *Tr* increased by 1.5 time and 1.2 times, respectively. Stomata are sensitive to the blue light spectrum (Kinoshita *et al.*, 2001; Jones 2014; Doi *et al.*, 2015), which our low–light LED unit contained. It therefore follows that the low–light LED supplemental lighting significantly increased *G*s induction.

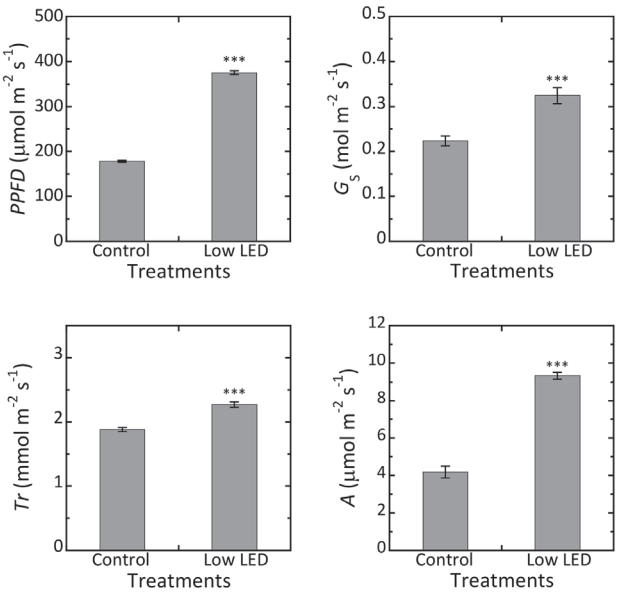

Fig. 5. Stomatal conductance (*G*s), transpiration rate (*Tr*), and photosynthetic rate (*A*) of the 3rd leaf of each strawberry plant under supplemental lighting (Low–light treatment) and no supplemental lighting (Control treatment). Photosynthetic photon flux density (PPFD) on the 3rd leaf is also shown. The means and standard error bars of 4 data sets are shown. Significance was determined by a *t*–test and is indicated by ***, where $P < 0.001$.

In many species, the opening of stomatal response arises when the light intensity increases (Shimazaki *et al.*, 2007). Additionally, the stomatal light–response curve typically reaches saturation near 400 μmol m^{-2} s–^{1}, but stomatal opening still occurs under low light intensity (Jones, 2014). For that reason, the increasing degree of *G*s and *Tr* were not the same as that of *A*.

CONCLUDING REMARKS

The low–light LED had a low initial cost and demon-

strated a suitable wavelength to the photosynthetically active radiation. This low–light LED in particular had a blue light spectrum, which can induce stomatal opening. Using this low–light LED as a supplemental lighting significantly improved light intensity and accelerated photosynthesis in strawberry leaves.

AUTHOR CONTRIBUTIONS

N. I. Muztahidin carried out the experiment, analyzed the data and wrote the manuscript. D. Yasutake designed the study, supervised the work, and provided facilities and resources. K. Hidaka supported in the design of the study and planned the work. Y. Miyoshi assisted the design of the study. A. Yoneda and K. Nagao participated in the behavioral experiments. M. Kitano, and T. Okayasu devised the project, the main conceptual ideas and proof outline. All authors discussed the results and contributed to the final manuscript.

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