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Horticultural crop production in plant factories with translucent solar cells and improvement of crops' marketability via supplementary monochromatic lighting

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Abstract

The rapid ageing of the population of Asian countries presents a demand for increased agricultural labor productivity. We are currently investigating the potential of a renewable energy-operated, energetically autonomous, sunlight combination-type plant factory for meeting this demand. In the factory, electricity is generated from translucent solar cells (TSCs) while improving the marketability of the horticultural crops cultivated within by supplementing the crops with monochromatic light using a portion of the generated power. Evaluation of the energy characteristics in a model glasshouse using TSCs revealed that sufficient electricity could be secured for supplementary monochromatic illumination. Subsequently, ultraviolet radiation–induced color change in chrysanthemum flowers and red light–induced early maturation of pea plants were investigated to evaluate the potential improvement of crop marketability from monochromatic light irradiation. The results demonstrated that the products' marketability could be improved with only minute power consumption.

Keywords: *crop marketability, monochromatic lighting, plant factory, translucent solar cell*

1. Introduction

Traditional family farming with low labor productivity has historically been practiced in many Asian countries, including Japan. However, as the population of Asian countries is aging rapidly, increasing the labor productivity of agriculture is a pressing issue. To solve this issue, the automation of agriculture, that is, the widespread use of plant factories, will become necessary. We have previously investigated the realization of a renewable energy-operated, energetically autonomous, sunlight combination-type plant factory (Watanabe *et al*., 2005). A conceptual diagram is shown in Figure 1. In this plant factory, translucent solar cells (TSCs) are installed in the roof of a glasshouse. Part of the incident solar energy is harnessed for power generation, while the light energy that passes through is used for by crops for photosynthesis. The electricity generated is used for management of the cultivation environment, such as ventilation of the glasshouse and operation of monochromatic lighting.

Plants use light not just for photosynthesis, but also as a signal of changes in their surroundings. Making use of this latter characteristic, we previously investigated the effect of supplemental blue light (460 nm) on the production of functional components in perilla planted in an unheated glasshouse, and found that the content ratio of a functional component, perillaldehyde, in plants grown with blue light was 60% higher than in control (Horibata *et al*., 2013). In this way, sunlight supplemented with additional monochromatic lighting has been shown to improve crops' marketability. Based on research revealing the specific photoreceptors present in plants, ultraviolet light (Christie *et al*., 2012), blue light (Ahmad *et al*., 1998, Christie *et al*., 1999), red light, and far-red light (Butler *et al*., 1959) are candidate wavelengths for supplementary monochromatic light expected to favorably affect crops. Crop marketability indicates superiority quality or value added in the market, such as early harvest time, unique flower color, excellent taste, or good nutritional properties. The specific properties important in the market depends on the type of crop, which span diverse categories such

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as flowers and ornamental plants, fruits and vegetables, or medicinal plants. Therefore, it is necessary to examine the effect of different kinds of supplementary lighting on various kind of crops with different economic values in order to refine and spread the use of supplementary monochromatic light.

In this study, we investigated the effect of supplementary monochromatic lighting in chrysanthemum flowers and pea plants for improving crop marketability, as well as the energy use characteristics of a sunlight combination-type plant factory equipped with TSCs.

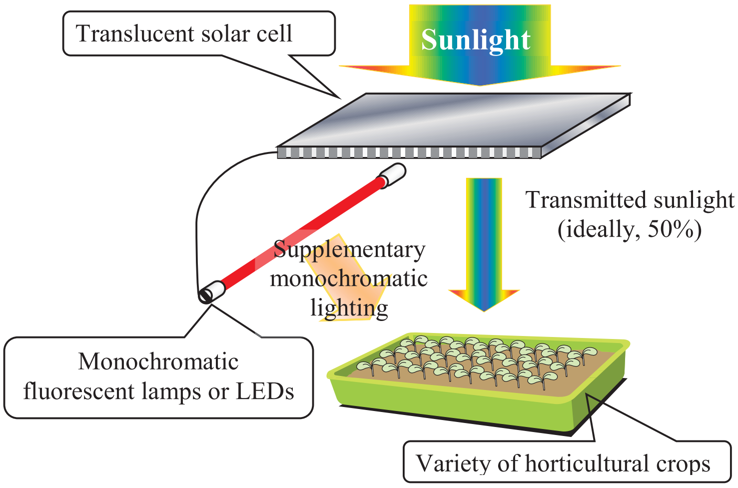


Figure 1. Conceptual diagram for divided use of solar energy in horticulture.

2. Material and Methods

2.1 Measurement of power output using a model glasshouse equipped with translucent solar cells

A model glasshouse (width 3.0 m, length 2.0 m, height 2.6 m; Kinokawa, Wakayama, Japan) was set up to evaluate the energy characteristics of a sunlight combination-type plant factory equipped with TSCs. As shown in Figure 2, TSCs totaling 6 square meters were mounted on the roof of the model glasshouse. Six plate of TSC model KN38 (Taiyo Industrial Co., LTD., Osaka, Japan) were used in this study. KN38 is originally a kind of the TSCs for building use and has been used for the outer wall of Suwon City Labor Welfare Center in Korea. Since numerous narrow slits (0.1 mm width) are in the non-transparent amorphous silicon layer at intervals of 8 mm × 1 mm, the overall light transmittance is about 10%. The output characteristics in one unit of about 1 square meter are as follows; the maximum power voltage is 54.5 V, the maximum power current is 0.66 A, and the maximum power is 36 W. Thus, the electromotive force of the entire 6 square meter panel is calculated at 3.96 A, 54.5 V. In terms of crop cultivation, a light transmittance of 10% is quite low, but as this was a preliminary model and as the incident scattered light from the normal-glass sides of the glasshouse may also be used in photosynthesis, tests were carried out in this light transmittance for the time being. In addition to the slit TSCs used in the present study, other TSCs designs with fine pores in the amorphous silicon solar cell (Takeoka *et al*., 1993) or using an organic thin-film solar cell (light transmittance 50%) (Lin *et al*., 2012) have been developed, but these were not yet available at the time that the present glasshouse was designed.

We performed model studies on the relation between insolation and power output and other parameters. A set of sensors for measuring solar operating current, solar operating voltage, amount of solar radiation, ambient air temperature, and humidity was affixed to the glasshouse. Data from each respective sensor were acquired at 10-minute intervals and transmitted to a monitoring system via wireless LAN. Unfortunately, due to system malfunctions, we were able to obtain the data of a consecutive few days only in March, August, November, and December in 2015. Despite this, however, we were able to establish approximate trends for the amount of power generated by the TSCs over one year.

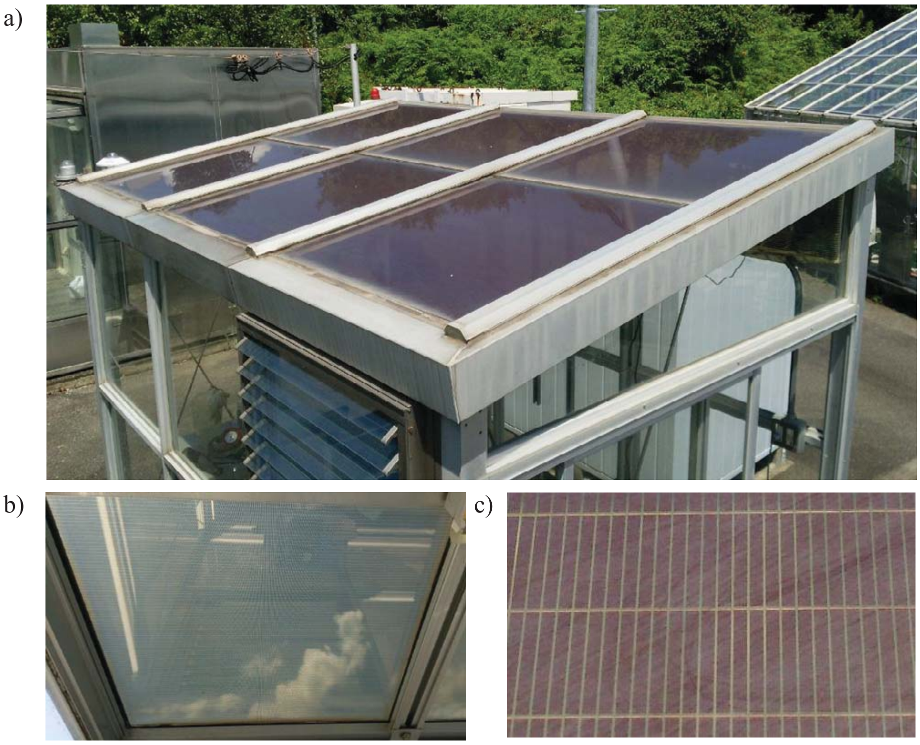


Figure 2. Model glasshouse used in this study.

a) Translucent solar cells installed in the roof of the glasshouse.
b) Light transmittance of the TSC (blue sky is visible through the solar cell).
c) Narrow slits in the amorphous silicon layer.

2.2 Improvement of marketability of horticultural crops by monochromatic lighting

2.2.1 Improvement of flower color of spray-type chrysanthemum by UV irradiation

Following this, we investigated the effects of supplementary monochromatic lighting on horticultural crops' marketability. Our first subject of investigation was flower color improvement in spray-type chrysanthemums (*Chrysanthemum morifolium* Ramat.), a flower with a history of symbolism tied to Japan. Spray-type chrysanthemums, as shown in Figure 3, are a category of cut flower that are tufted and of medium size. Colors range from reddish colors (purple, red, pink) generated anthocyanin-related pigments, yellowish colors (yellow, cream) generated by carotenoid-related pigments, orange colors, generated by both pigments, and white, without either pigment. Anthocyanin have superior antioxidant function and so are sometimes accumulated at high concentrations in tissues to be protected, such as young leaves. Biosynthesis of anthocyanin is particularly induced with oxidative stress due to UV irradiation (Chalker-Scott, 1999, Zhou *et al*., 2007). In light of these findings, we considered that darker color in chrysanthemum flowers would be induced by

UV irradiation.

Figure 3. Spray-type chrysanthemum.

Preliminary studies in red, red-purple, and yellow chrysanthemum varieties showed that flower color darkens upon UV irradiation in only those varieties that owe their color to anthocyanin-related pigments (red and red purple). Change in flower color was not observed at all in yellow carotenoid-related color varieties (data not shown). From this, the present study was targeted at anthocyanin-related chrysanthemums and two experiments were conducted to clarify the timing and intensity of UV irradiation required to induce a change in flower color.

In the first experiment, UV light of various intensity was used to irradiate buds before blooming and flowers after blooming in order to observe changes in flower color. A pink chrysanthemum variety, 'Elite Pink', was used, and 50 flowers cut at time of shipping, when the top terminal flower was just flowering (before-blooming) or at 1 week before shipping (after blooming) were obtained from Kinosato Agricultural Cooperative (Kinokawa, Wakayama, Japan). Before UV irradiation, in the before-blooming plot, all already-opened flowers were excised to retain the buds only, and in the after-blooming plot, all buds and partially opened flowers were excised to retain the newly bloomed flowers only. Here, different UV intensity conditions were effected by placing cut flowers at various distances from a single blacklight (FL40SBLB; Toshiba Lighting & Technology Co., Yokosuka, Japan; wavelength 270–430 nm, peak wavelength 350 nm). The UV irradiation intensity of the high- and medium- intensity plots were four and two times that of the low-intensity plot, respectively. UV irradiation was performed for 3 h (4–7 AM) daily. Petal color was evaluated from day 3 to day 12 after beginning UV irradiation in the before-blooming plot, and from day 1 to day 12 after beginning irradiation in the after-blooming plot. Color evaluation was performed using a fiber multichannel spectrometer (USB-4000; Ocean Optics Inc., Dunedin, USA) and the light reflected off petals upon irradiation with a standard halogen lamp was analyzed spectroscopically. Red color index was evaluated by using the relative intensity of red (wavelength; 645 nm) against green (wavelength; 500 nm) in the reflected light.

Based on findings that UV irradiation of buds was effective in changing flower color, in the following experiment, we attempted to assess the most effective developmental stage for inducing color change in flowers with UV irradiation in order to explore whether more efficient use of UV light could reduce irradiation. In this experiment, we used a different, pink-colored chrysanthemum variety, 'Kyonkyon'. A total of 150 flowers cut 2 weeks before shipping were obtained from Kinosato Agricultural Cooperative.

We designed 6 experimental plots, which each received 4 consecutive days of UV irradiation beginning at either 6, 8, 10, 12, 14, or 16 days before blooming; additionally, a control plot that received no irradiation was established. Due to the shorter UV irradiation period compared to the previous experience, the irradiation intensity and exposure hours per day were increased. Irradiation intensity was doubled by using two of the aforementioned 40 W blacklights, and exposure hours per day was doubled to 6 hours per day; however, this time was divided into three 2-h periods (5–7 AM, 1–3 PM, 9–11 PM) due to concerns about tissue damage caused by continuous UV exposure. After 5 days of blooming, redness of petals was evaluated as in the previous experiment.

2.2.2 Accelerated flower formation in pea plants using red light

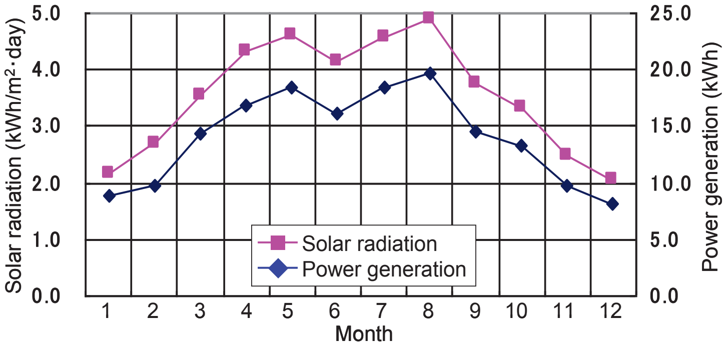
Our second subject of investigation is the acceleration of flower formation in garden peas (*Pisum sativum* L.). This variety of pea is the same species as green peas, but is eaten at a slightly more mature phase of development. In Japan, forced pea culture is practiced using incandescent lamps, allowing for harvest to occur from early spring to early summer. Earlier flower formation leads to earlier harvesting and shipment, as well as higher market value due to the ability to supply a savored spring vegetable to expectant consumers earlier in the season. Flower formation in plants is controlled by the length of the continuous dark period. When plants are exposure to light for a short duration during the night, the continuous dark period is interrupted and shortened, falsely creating conditions that mirror the arrival of spring. In the case of peas, this manipulation leads to flower formation. One red light receptor pigment, phytochrome, plays a principal role in measurement of the length of the continuous dark period, and we therefore attempted to accelerate flower formation in peas by exposure to red light at nighttime.

In this experiment, we used two pea varieties, 'Kishu-usui' and 'Kinokagayaki'. 'Kinokagayaki' is an improved variety of 'Kishu-usui' developed for with earlier flower formation. An LED array (1200 × 600 mm) was established using 230 high-brightness Flux LEDs (CH-LB3B-2; Peace Co., Koshigaya, Japan; 645 nm) as the red light source. A series of test plots with different red light intensity was established by placing 8 parallel plant containers (700 × 300 mm) at various regularly spaced intervals from the array, with the closest at 1500 mm. A control plot was also placed in an unexposed location. A total of 8 pea seeds were planted in each container on October 28th, and days from seeding to first bloom was observed. All experimental plots were irradiated with red light for 3 h nightly (1–4 AM), resulting in a continuous dark period of less than 8 hours, which is even shorter than the dark period on the shortest night of the year, the summer solstice.

3. Result and Discussion

3.1 Power output measurement using a model glasshouse equipped with a translucent solar cell

Figure 4 shows the monthly insolation for an average year in Wakayama, Japan, and the estimated amount of power generation calculated based on this solar radiation and the standard parameters of the TSCs provided by the supplier. The maximum estimated monthly power generated was 20 kWh in August, and the minimum was 8 kWh in December. Figure 5 shows the diurnal variation in power generation measured during 4 consecutive days in August or December, 2015. The maximum value of power generated in one day reached about 40 W in summer and about 20 W in winter. Of course, power generated on cloudy and rainy days was lower than that generated on days with clear weather.



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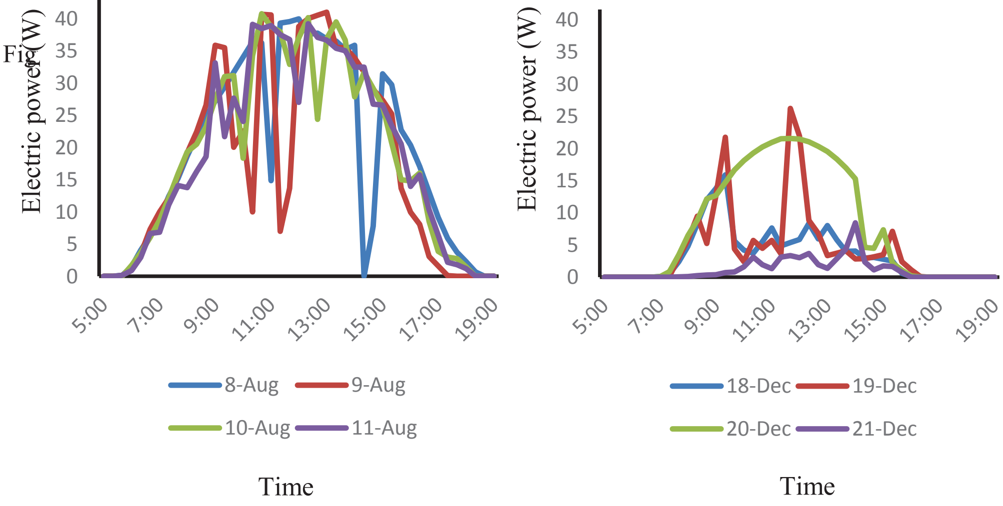


Figure 5. Diurnal variation of power obtained from TSCs at Kinokawa, Wakayama.

Table 1 shows the amount of global solar radiation and daily power generation measured for 2 or 4 consecutive days in March, August, November, and December, 2015. Global solar radiation shown is based on the public database of the regional meteorological observatory located closest to the experimental site, in Osaka, Japan (Japan meteorological agency website, http://www.data.jma.go.jp/gmd/risk/obsdl/). On a clear day, the amount of daily power generated was 0.827 kWh in summer (8 August) and 0.351 kWh in winter (20 December). On a cloudy/rainy day, daily power generated declined to as low as 0.051 kWh (21 December). Figure 6 shows the correlation of the amount of global solar radiation and the amount of daily power generation. The amount of daily power generation increased proportionately to the amount of global solar radiation. The conversion efficiency of the entire apparatus was calculated to be about 2%.

Table 1. Global solar radiation and daily power generation measured in continuous 2 or 4 days in March, August, November and December 2015.

Date	Global solar radiation (MJ/m^2・day)	Daily power generated（kWh)
28 March	22.80	0.618
29 March	4.49	0.120
8 August	23.96	0.827
9 August	25.78	0.760
10 August	22.74	0.821
11 August	23.30	0.813
13 November	5.13	0.131
14 November	3.24	0.080
15 November	7.12	0.192
16 November	13.10	0.401
18 December	6.16	0.149
19 December	8.42	0.183
20 December	11.34	0.351
21 December	2.20	0.051

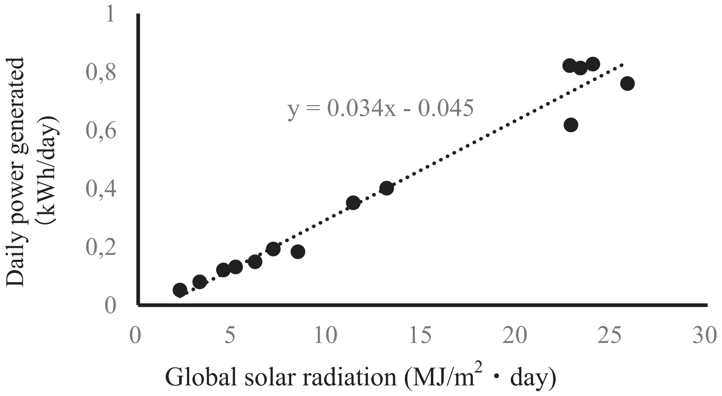
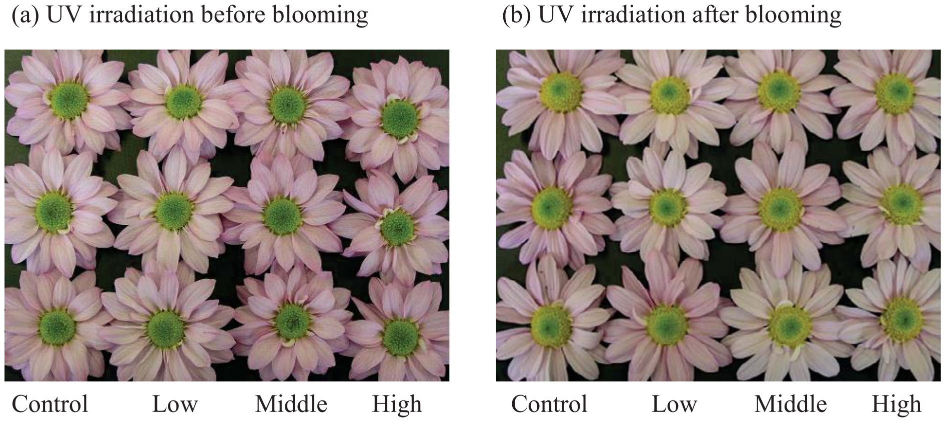


Figure 6. Correlation between the amount of global solar radiation and the amount of daily power generation.

3.2 Improvement of flower color in spray chrysanthemums by UV irradiation

Figure 7 shows the flower color of chrysanthemums subjected in various intensities of UV irradiation before or after blooming. For the group irradiated before blooming, the color of the high- and medium-intensity plots, but not the weak-intensity plot, was significantly more intense than that of the control plot. In contrast, in group irradiated after blooming, no significant differences in flower color were observed between any of the plots and the un-irradiated control. These results suggest that UV irradiation before blooming is necessary for induction of change in flower color in chrysanthemums.


(a) UV irradiation before blooming

(b) UV irradiation after blooming

Figure 7. Flower color of chrysanthemums subjected to different intensities of UV irradiation before blooming (a) or after blooming (b).

In light of this result, we irradiated buds with UV light for 6 h/day for 4 consecutive days beginning between 19 and 6 days before blooming. Figure 8 shows the change in flower color in each plot. UV irradiation 13 to 10 days before blooming or 11 to 8 days before blooming resulted in significant change in flower color compared to the control plot. Taken together, this indicates that the period of 11 to 10 days before blooming, the overlapped period of these two plots, results in marked change in flower color. Because this period is equal to a few days prior to the general shipment time for cut flowers, it is economically preferable to perform UV irradiation for cut flowers harvested at a slightly earlier time than performing UV irradiation for an entire greenhouse.

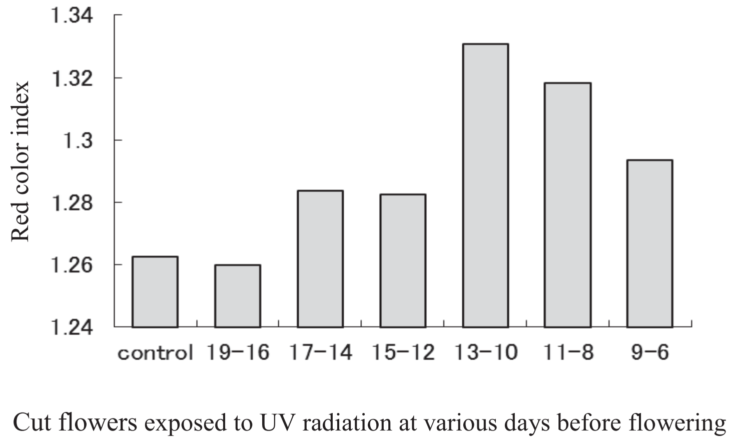


Figure 8. Flower color of chrysanthemums when buds were exposed to 4 days of UV irradiation at different developmental stages.

3.3 Accelerated flower formation in pea plants using red lighting

Figure 9 shows the effect the intensity of red light used for dark period interruption on the duration from seeding to blooming of the first flower cluster. In ‘Kishu-usui’, days to blooming was approximately 150 days in the control group, which was reduced by 10 days by dark period interruption. In ‘Kinokagayaki’, this reduction of the days to blooming in groups with dark period interruption was about 20 days. In both varieties, this reduction was maximized by irradiation intensity of 2 µmol/m^2/s, but no further effects were observed when the intensity increased beyond this point up to about 10 µmol/m^2/s. This suggests that the minimum value of the red light intensity used in dark period interruption required to accelerate flower formation in peas is as low as 2 µmol/m^2/s.

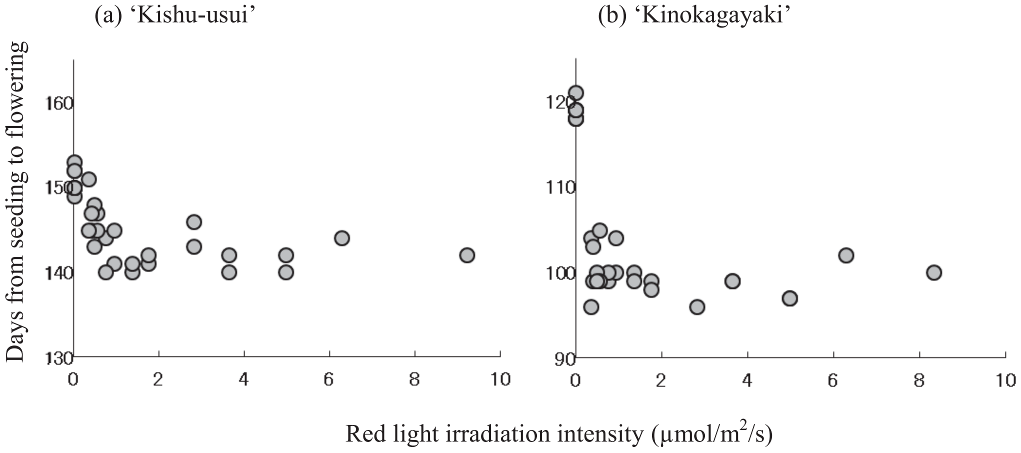


Figure 9. Effect of intensity of red light used for dark period interruption for promoting flowering in pea plants.

4. Conclusion

The power output of the model glasshouse equipped with TSCs, as investigated in 2015, was greatest on 8 August, at 0.827 kWh/day, and lowest in 21 December, at 0.051 kWh/day. In comparison, 0.240 kWh/day (40 W × 6 h/day) of electricity was used to induce chrysanthemum flower color change and 0.099 (33 W × 3 h/day) kWh/day was required to accelerate pea plant flower formation. Because we used a 40 W fluorescent tube (blacklight) with relatively high power consumption for chrysanthemum experiments, power consumption per day was as high as 0.240 kWh/day. However, since it was possible to narrow the irradiation period to only 4 days, the power supplied over multiple days would still be sufficient to power the lights for 4 days, even in winter, if appropriate energy-storage systems are available. For peas, we used daily irradiation consuming 0.099 kWh/day of electricity; however, as the required irradiation intensity necessary for acceleration was determined to be 2 µmol/m^2/s, the actual amount of electricity needed is estimated to be only 0.050 kWh/day. The present TSCs are capable of supplying this amount of electricity, and generally speaking, are fully capable of providing energy within this range.

The TSCs used in our study were amorphous solar cells with slits to give 10% transmittance; however, to grow healthy crops under TSCs, light transmittance of around 50% is desired. As stated by Lin *et al.* (2012), although TSCs with around 50% transmittance have been produced experimentally, their power generation performance is corresponding lowered as light transmission is increased. In the future, we must investigate the economic performance of our cultivation method when higher transmittance units are used.

The average amount of solar radiation in the plain part of Japan is about 1300 µmol/m^2/s. In contrast, up to about 800 µmol/m^2/s can only be used for photosynthesis of crops. Excessive solar radiation will increase leaf temperature, accelerate respiration, inhibit growth of the crop, and cause various obstacles due to production of active oxygen species. Therefore, in this study, we proposed to convert a part of excessive solar energy into electric energy by TSCs. And we expected to obtain some economic benefits by irradiating crops with red light that regulates the circadian rhythm of plants, or with ultraviolet light that induces the production of secondary metabolites. As a result of this study, we have shown that characteristics of horticultural crops can be changed by minute photostimulation of plants. The electricity required for these processes was obtainable from TSCs equipped within the cultivation facility. The marketability of products from sunlight combination-type plant factories can be expected to improve when these methods are used.

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