



STUDIES ON THE CULTIVATION OF THE STRAWBERRY UNDER THE LIGHT TRANSMISSION TYPE SOLAR CELL CONDITION

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ABSTRACT

We examined the cultivation of the strawberry under the light transmission type solar cell (panel) condition that absorbs the ultraviolet light for electricity, and passes ca. 20% of visible light from 400nm to 800nm for photosynthesis. Though the color of leaves under the solar cell was lighter than that under control area, the length and width of the leaves were not so different among the treatments.

On the other hand, the number of honeybees visiting flowers and SSC were significantly correlated with the integrated photon flux density, and the number of fruits harvested and the yield showed strong correlation coefficient with it.

However, the coefficient of correlation between the number of flowers bloomed or fruit size and the integrated photon flux density were relatively low, suggesting that the light interception by the solar cell does not affect much on the number of flowers bloomed or fruit size.

As the yield and the quality of the strawberry fruits decreased with the light intensity by the light transmission type solar cell, the yield and the quality of the fruits can be improved by widening the space between the panels.

Originally, the transmission type solar cell had been expected not only as ecological role of power generation, but also as the source of light in a room. Here, the authors propose an additional role of the transmission type solar cell as a roof panel of a greenhouse.

Key Words: light transmission; shading; solar cell; strawberry.

INTRODUCTION

Two energy issues have come to the hot topic ; one is the environmental disruption of the global scale such as the greenhouse effect by carbon dioxide (CO₂) evolving from the fossil fuel and the other is the shortage of the fossil fuel (Armin, 2009; Zahedi, 2006).

Recently, the photovoltaic generation by solar cell that converts solar energy to electric power and doesn't evolve the CO₂ has been paid attention as it is a kind of renewable energy and the majority of the composition material is recyclable. Especially, after the accident of the Fukushima nuclear power plant by the Great East Japan Earthquake and the subsequent tsunami disaster on March 11, 2011, the risk of the nuclear power generation drew the public's attention. Then the solar cell has been on the news often as renewable energy that not only doesn't depend on the fossil fuel, but also is free from the risk of radioactive waste. Therefore, many countries including Japan as well as Germany and Italy have begun shifting from nuclear power generation to renewable energy.

Japan used to produce ca. 50% the solar cell panels in the world until 2004. However, after 2005 when the New Energy Foundation (NEF) finished subsidies, the domestic market decreased and China, Germany and Taiwan overcame Japan from 2008 when the world share of Japan decreased to 18%. Then the Ministry of Economy, Trade and Industry of the Japanese Government launched a new solar power-generated electricity purchasing system on November 1, 2009 to promote the renewable energy policy.

There are many reports on the effects of light intensity and light quality on the growth (Yanagi et al., 1996 ; Nhut et al., 2003), on the floral initiation (Yanagi et al., 2006) and on the amount of some compounds (Atkinson et al., 2006) of strawberry. However, the reports on the cultivation of strawberry under the light passed through solar cells.

On the other hand, Oerlikon Solar Corporation in Swiss developed the light transmission (= see-through) type solar cells. The thin film solar cell generates the power using a part of sunlight and can pass the rest of sunlight through. Therefore, it is ideal if we use not only the electric power generated for the strawberry cultivation such as light culture, but also the transmitted light for the cultivation of crops, as the only method to decrease CO₂ is photosynthesis by plants.

In this study, we investigated the possibility of the cultivation of strawberry under the light transmission type solar cell.

MATERIALS AND METHODS

This experiment was carried out on the plant bench, 0.3 m in width, 34 m in length and 0.9 m in height in a 24 m × 51 m green house of Kinouchi farm, Tateno, Minami Aso-mura, Kumamoto, Japan from September, 2010 to April, 2011. The solar cells used in this experiment were light transmission type thin silicon film laminated by glass (WD-C-GF-0902, Sunwell Solar Ltd.). The solar cell speculation was 1.1 m in width, 1.3 m in length, 6.8 mm in thickness and 25 kg in



weight. The solar cell panels were installed on the southern roof of the greenhouse (Fig. 1). By the simulation of the area shielded from sunlight in December, the second and third benches from the southern side of the house were selected for three treatments. Treatment 1 was a cultivated area shaded strongly by twenty-four (3×8) solar cell panels without space. Treatment 2 was also a cultivated area shaded by the same number of panels with 40 cm space. The control area was a cultivated area not shaded by any solar cell panels.

In each treatment, twelve strawberry plants, 'Toyonoka', were transplanted 20 cm apart in 2 rows on the bench on September 20th, 2010 and the cultivation practice was carried out as conventional. The soil medium used was 30% bark, 50% red loam soil and 20% peat. As basal fertilization, nitrogen, phosphate, potassium and calcium were applied 5, 7, 5 and 1.2kg/10a, respectively. Liquid fertilizers were applied as additional fertilization; nitrogen, phosphate and potassium were totally 11, 7 and 9kg/10a, respectively. Additional light culture started from November 8th and stopped on March 3rd for three hours except January 10th to 22nd for four hours.

European honeybee, *Apis mellifera*, was released as a pollinator for the strawberry. The length and width of the largest leaf, number of leaves and chlorophyll contents (SPAD value) were investigated every other week after transplanting. Chlorophyll contents were measured by chlorophyll meter (Konica Minolta SPAD-502).

Number of flowers bloomed and height, diameter, weight, hardness, color, quality, insect damage, and sugar contents (soluble solid contents, SSC) of the fruits harvested were investigated on every Monday, Wednesday and Friday from November 26, 2010 to April 22, 2011. Sugar contents were measured by digital Brix refractometer (Atago PR-201 α).

Temperature and relative humidity were monitored by Hygrochron KN Laboratories, Inc. every minute and photon flux density was measured by photon flux meter (ML-020P, EKO Instruments Co. Ltd.) every 10 seconds and sunlight spectrum was measured by spectroradiometer (MS-720, EKO Instruments Co. Ltd.).

To make clear the behavior of the honeybee under the solar cell, the number of honeybees visiting flowers and its time were surveyed by naked eyes on a fine day, December 4, 2010 from six in the morning until sunset.

The photon flux densities were integrated and the correlation coefficients between the data of the strawberry properties and the integrated photon flux density were analyzed.

RESULTS AND DISCUSSION

The light transmission type solar cells used in the present study mainly cut the ultraviolet wavelength of the solar spectrum and passed 20% of the visible region of sunlight in average. Yanagi et al. (1996) reported that the average photosynthetic efficiency of strawberry under red light was 2.5 times higher than that under blue light. Nhut et al. (2003) reported that plantlet growth of both in vitro culture and after transferring to soil was best at 70% red + 30% blue LEDs and the optimal light intensity was $60 \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$. Yanagi et al. (2006) studied the effects of light quality of LED spectrum on the floral initiation of *Fragaria chiloensis* and found that far-red light (735 nm) initiated the flower buds, but blue and red light not. The solar cells passed the red light (620-750nm) through more than blue light (450-495nm) or green light (495-570nm), suggesting that the solar cells used in this experiment had an advantage for the photosynthesis (Fig. 2).

Changes in the leaf sizes, the number of leaves and chlorophyll contents (SPAD value) of strawberry plants are shown in Figure 3. The leaf sizes and the number of the leaves of the treatments 1 and 2 shaded by the solar cell panels were not so different from those of the full sunshine control, though Jurik et al. (1982) reported that strong light intensity change the leaf thicker, maximum net CO₂ exchange rate and leaf size larger than weak light intensity. While chlorophyll contents of the control area were more than those under the solar cells.

Changes in the photon flux density and temperature on December 4, 2010 when the behavior of the honeybees were surveyed are shown in Figure 4. Visiting frequency of the honeybees and the correlation between the number of honeybees visiting flowers/plant and integrated photon flux density are shown in Figure 5. The sun rose at 7:00 and set at 17:20 (Fig. 4). However, the photon flux density was low until 11:00, as the greenhouse located at the western mountainside of Mt. Aso. As it was fine, the maximum photon flux density was $969 \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ and at noon time the photon flux density was $840\text{-}950 \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ (Fig. 4C) at the control area. Periodic down of the photon flux density were caused by the shadow of steel frame (Fig. 4C). In the treatments 1 and 2, narrow and wide periodic peak of the photon flux density were observed when sunlight passed through the space of the cell panels (Fig. 4A, B). Then, the spot maximum photon flux densities of the treatments 1 and 2 were 702 and $794 \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, and the range of the photon flux densities at noon time were $90\text{-}130$ and $160\text{-}200 \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, respectively. The integrated photon flux densities of the control area, treatments 2 and 1 on December 4, 2011 were 1.2×10^7 , 5.1×10^6 and $3.2 \times 10^6 \mu\text{mol} \cdot \text{m}^{-2}$, respectively.

As honeybees visit flowers under the temperature condition between 18°C and 30°C, they were observed visiting flowers between 11:00 and 16:00 and the number of honeybees visiting flowers increased with the photon flux density (Fig. 5A). The total number of honeybees visiting flowers of the full sunshine control area and the treatments 2 and 1 shaded by the solar cells with and without spaces were 7.2 ± 1.2 , 2.0 ± 0.5 and 1.1 ± 0.3 , respectively, suggesting that it was positively related with the integrated photon flux density. As honeybee has color sensory perception for UV (peaking at 340 nm), blue (peaking at 463 nm) and green (peaking at 530 nm) colors and does not have sensing ability to long wavelength light, they stopped their activities under the solar cells which intercepted UV light (Srinivasan, 2010). As only three treatments were prepared in this experiment, the degree of freedom (df) was $3-2=1$, which requests more than 0.997 of the coefficient of correlation for the significant correlation. The coefficient of correlation between the integrated photon flux density of the day and the total number of honeybees visiting flowers was $R=0.998$, indicating that it was significant (Fig. 5B).



Though the first flower started blooming on November 26, 2010 at all of the three treatments, subsequent blooming and fruit setting under the solar cells were delayed compared to the control area. The harvest of the first flower cluster started on December 10, 2010 and ended on January 7, 2011 at the control area, while at the treatments 2 and 1, it started on December 13 and December 22 and ended on January 24 and February 16, respectively. The integrated photon flux densities of the control area, treatments 2 and 1 from September 23, 2010 to April 22, 2011 were 2.11493263×10^9 , 1.00168005×10^9 and $7.0509397 \times 10^8 \mu\text{mol} \cdot \text{m}^{-2}$, respectively.

Figure 6 shows the correlations of number of flowers, number of fruit harvested, fruit height, fruit width, fruit weight, yield, and SSC of the strawberry harvested with the integrated photon flux density from September 23, 2010 to April 22, 2011.

The number of flowers bloomed per plant was not so different between the control (43.1 ± 4.8) and the treatment 2 (43.0 ± 4.8) or treatment 1 (36.7 ± 2.5) and the coefficient of correlation between the integrated photon flux density and the number of flowers bloomed was not so high, $R=0.672$ (Fig. 6a), indicating that the light interception by solar cells positively affected the number of flowers bloomed, but not so strong.

While the number of fruits harvested per plant was decreased to 24.1 ± 1.4 at the treatment 2 and to 19.7 ± 1.5 at the treatment 1 from 33.1 ± 3.6 at the control area, as the light intensity decreased (Fig. 6b). Therefore, the coefficient of correlation between the integrated photon flux density and the number of fruits harvested was quite high, $R=0.992$, though it was not significant (less than 0.997). The difference of the two results between the number of flowers bloomed and the number of fruits harvested per plant was considered that it was derived from the number of honeybees visiting flowers.

Compared to the fruit height at the control area, 34.1 ± 3.0 mm, those under the solar cells were relatively small but not so different, 32.8 ± 0.7 mm at the treatment 2 and 30.3 ± 0.7 mm at the treatment 1 (Fig. 6c). The coefficient of correlation between the integrated photon flux density and the fruit height was not significant ($R=0.899$). As well as the fruit height, fruit width harvested at the control area, 28.2 ± 2.5 mm, was relatively wider than 27.6 ± 0.7 mm at the treatment 2, and 25.9 ± 0.5 mm at the treatment 1 (Fig. 6d). The coefficient of correlation between the integrated photon flux density and the fruit width was not significant ($R=0.836$). Therefore, the fruit weight at the control area, 11.4 ± 1.1 g, was also heavier than those under the solar cells, 10.8 ± 0.6 g at the treatment 2, and 9.1 ± 0.5 g at the treatment 1 (Fig. 6e). The coefficient of correlation between the integrated photon flux density and the fruit weight was not significant ($R=0.845$). Thus, the effect of light interception on the fruit size and weight was relatively small.

On the other hand, soluble solid content (SSC) was 8.5 ± 0.7 at the control area and decreased, 7.5 ± 0.1 at the treatment 2, and 7.0 ± 0.2 at the treatment 1, as the integrated photon flux density decreased (Fig. 6d). The coefficient of correlation between the integrated photon flux density and the fruit quality (SSC) was quite high though it was not significant ($R=0.974$). The yield of the strawberry at the control area, the treatment 2 and the treatment 1 were 3.09 ± 0.32 t/10a, 2.14 ± 0.15 t/10a and 1.46 ± 0.10 t/10a, respectively (Fig. 6f). Then the coefficient of correlation between integrated photon flux density and the yield was $R=0.9971$, indicating that the light interception affected the yield of strawberry significantly.

In the present experiment, not only the possibility of the practical strawberry cultivation under the light transmission type solar cell which passes ca. 20% of 400-800 nm sunlight through, but also the basic findings on the growth of strawberry under weak light condition were obtained. First of all, the growth of strawberry under solar cells was better than expected and the looking of the fruits, the color and size, were even better. However shading by the solar cells delayed the maturity of fruits and decreased the amount of yield and sweetness.

The significant correlations with the integrated photon flux density were observed only on the number of the honeybees visiting flowers and SSC. Quite high correlation coefficients with the integrated photon flux density were observed on the number of fruits harvested, $R=0.974$, and the yield, $R=0.991$, though they were not significant. On the other hand, positive correlations with the integrated photon flux density were observed on the number of flowers bloomed of fruit size and weight, though the coefficient was relatively low.

Photon flux density plays an important role on the cultivation of strawberry, especially not only on the yield but also on the coloring of strawberry fruits. Strawberry changes vegetative and reproductive growth by the photoperiodic and/or temperature response. Hong, et al. (2010) reported that fruiting efficiency and solar irradiance was positively correlated. In the present study, clear differences were not observed on the leaf size, the number of flowers, fruit size and fruit weight between the treatments.

On the other hand, many plants can survive even under dark condition such as ferns, oxalis, African violet or taro whose light saturation point was assumed less than 1,000 ft-c ($=10,764$ lux) and the compensation point was 50 ft-c ($=538$ lux). Johnson et al. (2000) reported that *Trichomanes speciosum*, a European fern species, grew under 0.01% sunlight condition. Actually, at a leaf ornament farm in Kumamoto, Japan, they grow the plants under 85% shading condition. Therefore, the light transmission type solar cell used in the present study is considered good enough for the crops because it pass through 20% of sunlight.

As the yield and the quality of the strawberry fruits decreased with the light intensity by the light transmission type solar cell, the yield and the quality of the fruits can be improved by widening the space between the panels. Therefore, even the possibility of practical use of it for the cultivation of strawberry is still remained. Originally, the transmission type solar cell had been expected not only as ecological role of power generation that doesn't evolve any carbon dioxide, but also as the source of light in a room. Here, the authors propose a new additional role of the transmission type solar cell as a roof panel of a greenhouse.

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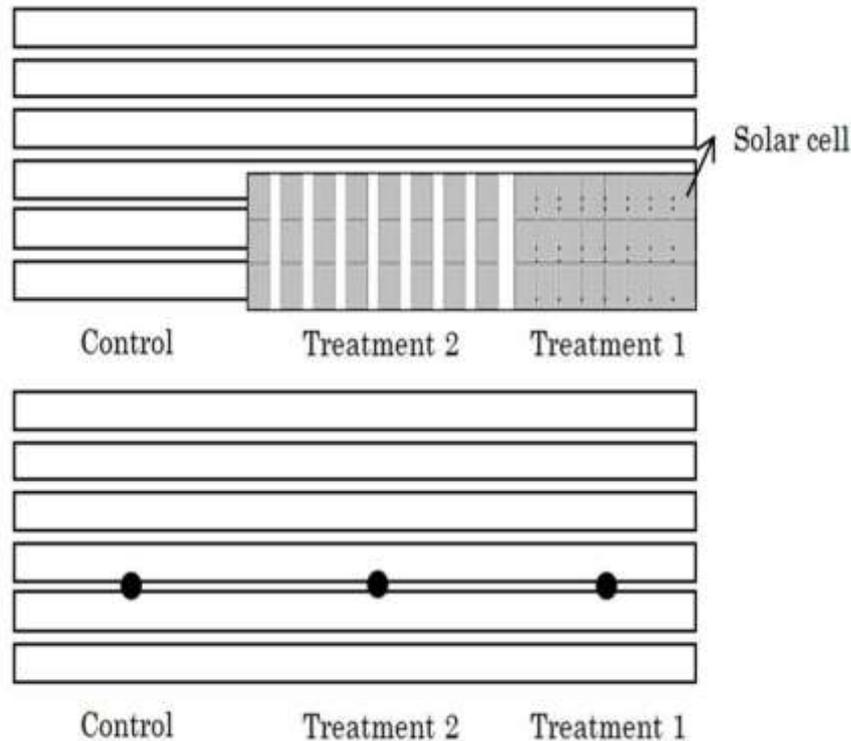


Fig. 1. Solar cells on the roof of greenhouse and position of the photon flux meter (●).

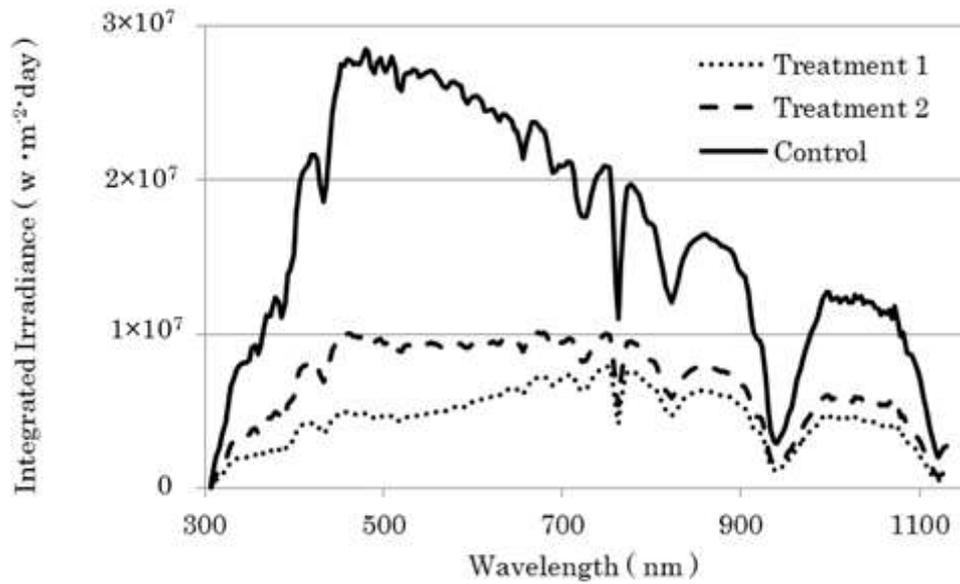


Fig. 2. Spectral irradiance characteristics under solar cell.

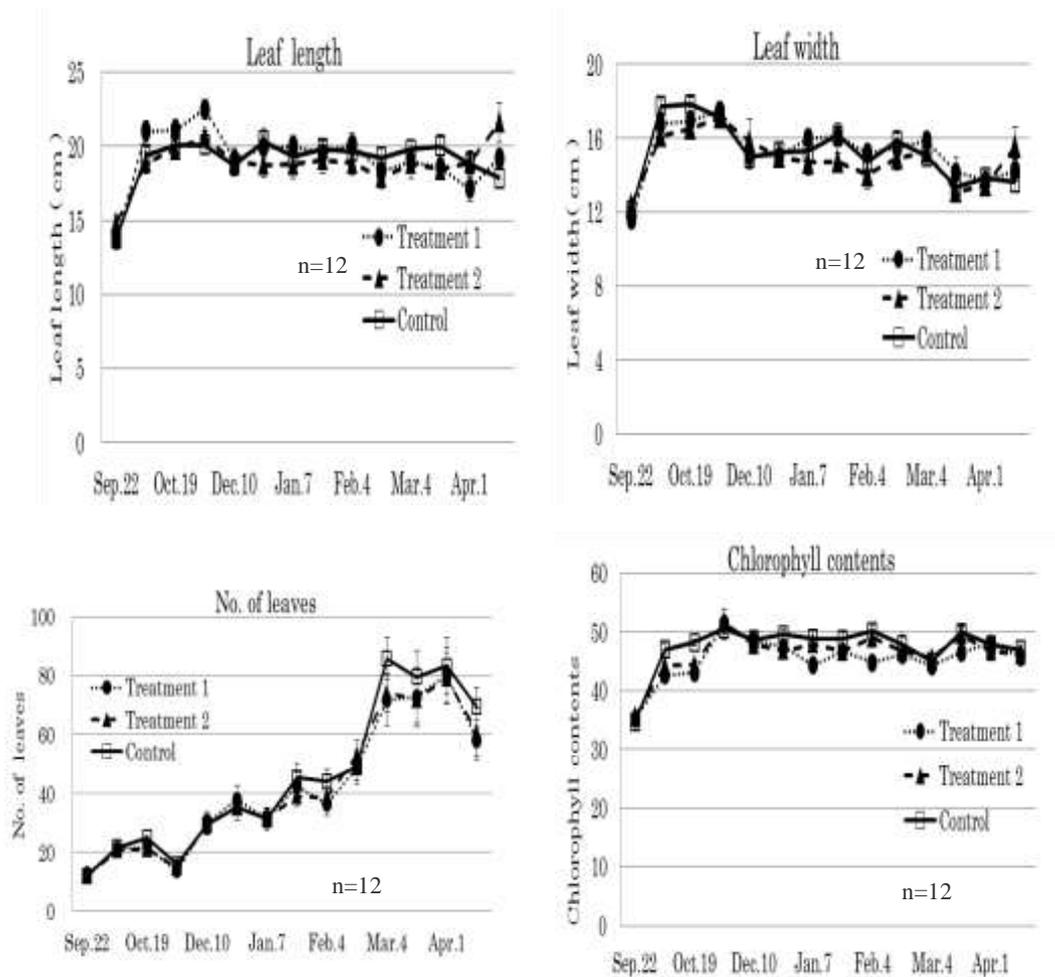


Fig. 3. Effect of shading by solar cells on the leaf length and width, number of leaves and chlorophyll contents of strawberry. Mean \pm standard error.

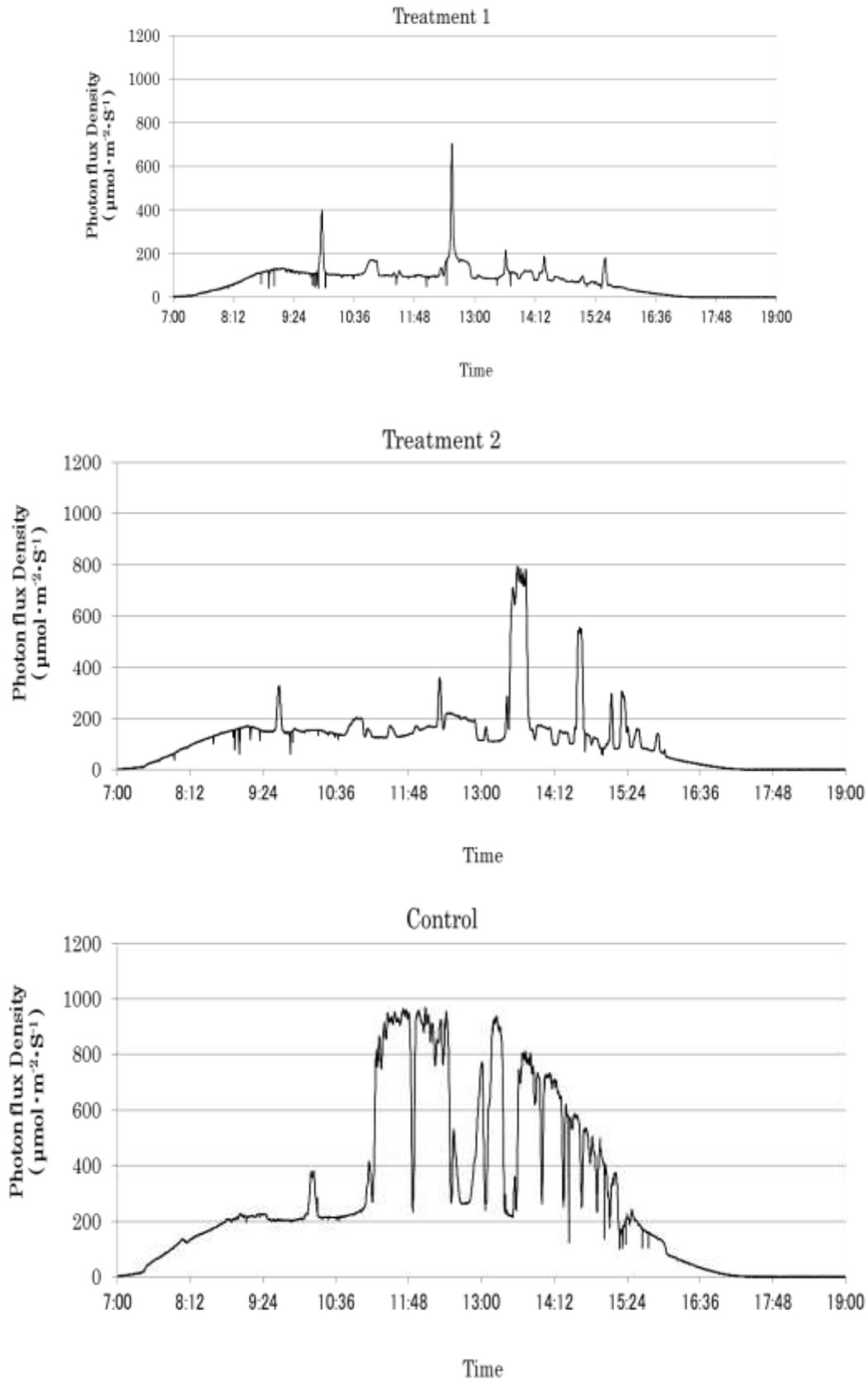


Fig. 4. Daily changes in the photon flux density on December 4, 2010.

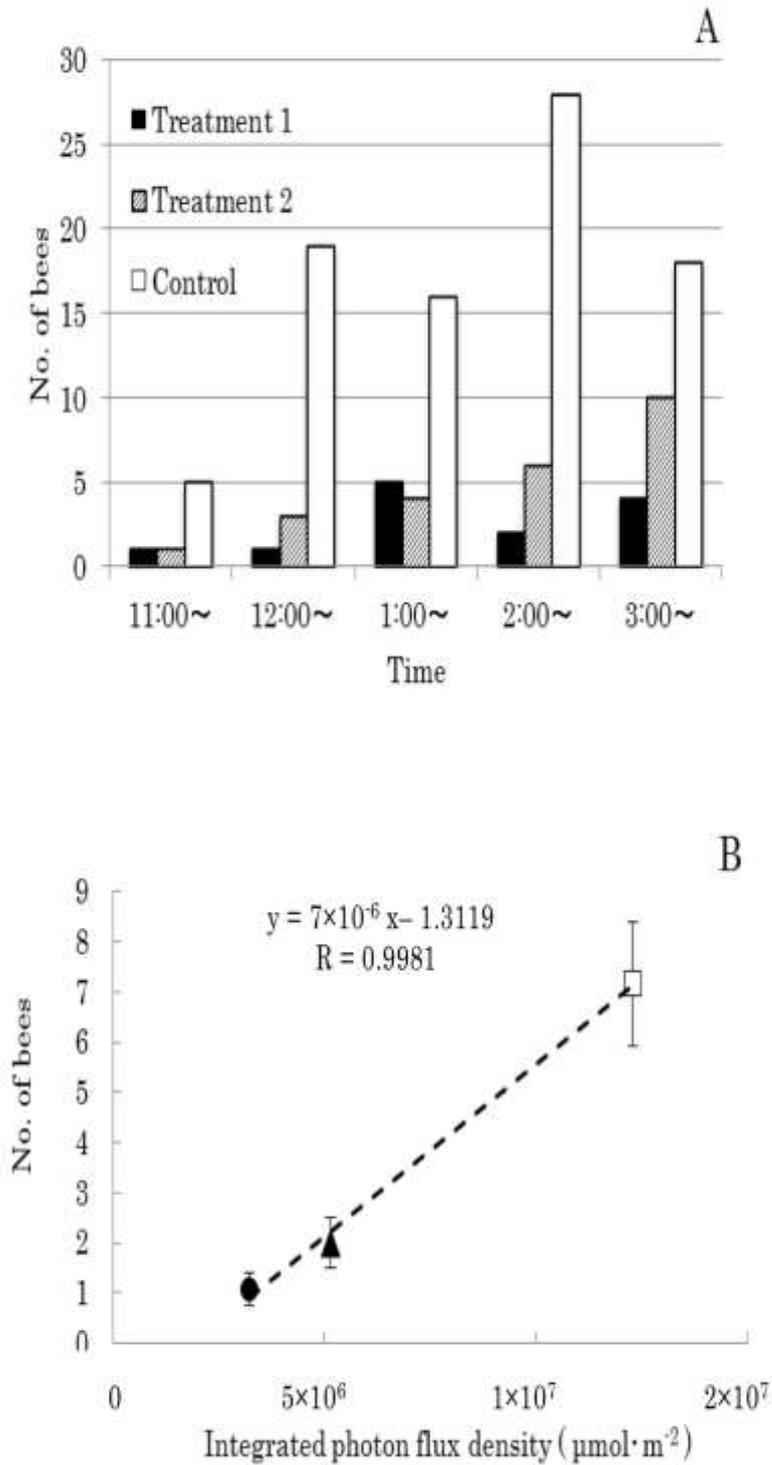


Fig. 5. Visiting frequency of honeybees to twelve strawberry plants of the treatments during every one hour (A) and the correlation between the number of honeybees visiting flowers / plant and integrated photon flux density (B) on Dec. 4, 2010.

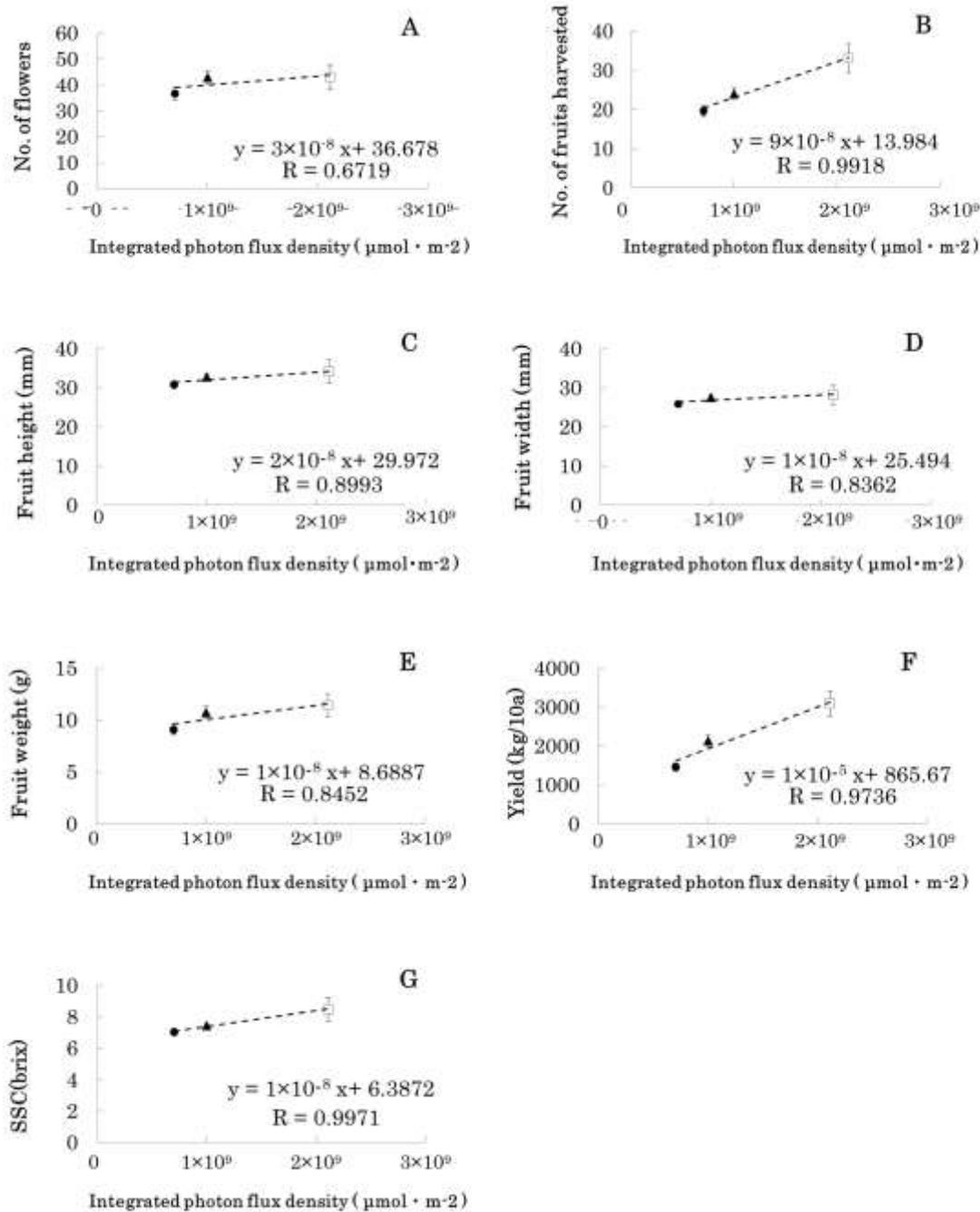


Fig. 6. Correlation between the integrated photon flux density and strawberry characters from September 26, 2010 until April 22, 2011 and several properties of strawberry. A ; No. of flowers, B ; No. of fruits harvested, C ; Fruit height, D ; Fruit width, E ; Fruit weight, F ; Yield, G ; SSC. Mean \pm standard error.