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Improvement in lettuce growth by light diffusion under solar panels

Akira TANI *, †, Suguru SHIINA *, Kazuki NAKASHIMA * and Makio HAYASHI **

* Institute for Environmental Sciences, University of Shizuoka, 52−1 Yada, Shizuoka 422−8526, Japan
** School of High-Technology for Human Welfare, Tokai University, 317 Nishino, Numazu 410−0395, Japan

Abstract

Power generation by roof-mounted photovoltaic (PV) modules may provide additional income to farmers if the crop production is comparable to production under normal greenhouse conditions. However, fluctuating irradiance caused by the partial shade of PV modules has been reported to reduce crop production. In the present study, we have shown for the first time the possibility of improving lettuce growth by using light diffusion films under roof-mounted PV modules. The effects of different light conditions (direct but fluctuating and diffused but uniform irradiations) under PV modules on the morphology, yield, and photosynthesis of hydroponically grown lettuce were investigated. Lettuce growth was inhibited, resulting in lower dry weight and relative growth rate (RGR) with longer leaves, under the fluctuating light by roof-mounted PV modules compared to normal greenhouse conditions. On the other hand, the ratio of leaf width to length increased under diffused light conditions and the values were comparable to those in the control in spring, summer, and fall cultivations. Although the net photosynthetic rate of fully expanded leaves of lettuce grown under diffused light was lowest, their dry weight and RGR were comparable to the control in summer and fall cultivations. Diffused light might penetrate into the lower layers of the leaf canopy, thereby increasing the CO_2 fixation of the whole canopy. Our results suggest that the application of light diffusion films is a viable option for improving crop productivity under roof-mounted PV modules.

Key words: Diffused light, Fluctuating irradiation, Lettuce, Net photosynthetic rate, Photovoltaic module.

1. Introduction

The application of photovoltaic (PV) modules in agricultural land was first proposed in 1982 (Goetzberger and Zastrow, 1982). In the first decade of the 21st century, PV modules were used in small areas of greenhouse roofs to produce electricity for the operation of low-power consuming devices, such as the ventilation system (*e.g.* Yano *et al.*, 2007). Since 2010, crop cultivation experiments have been conducted under roof-mounted PV modules. The partial shading provided by PV modules has been reported to negatively affect the growth of Welsh onions (Kadowaki *et al.*, 2012) and tomatoes (Ureña-Sánchez *et al.*, 2012). In these studies, the roof area covered by PV modules was ~10 %, resulting in a small decrease in yield.

However, some crops, including lettuce, grown in a greenhouse do not always require high light intensity, and their photosynthetic rate saturates at ~1/4th of full sunlight during summer, *i.e.* ~500 μmol m^{-2} s^{-1} (Caporn, 1989). For the cultivation of such plants, a larger shaded area may be applied to the greenhouse. Except for white asparagus cultures (Tudisca *et al.*, 2013), no attempts have been made to grow shade-tolerant plants under PV modules covering a large area of the greenhouse roof.

Frequent fluctuations in light intensity are caused by the shade under the PV modules and the direct light transmitted through the transparent glass between the PV modules (*e.g.* Yano *et al.*, 2010). Use of light diffusion films may be an option to make the light distribution uniform for improving plant growth as the application of light diffusion films to normal green-

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[†] Corresponding Author: akiragrc@yahoo.co.jp

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houses improved the yield in green peppers (*Capsicum annuum*) (Chun *et al*., 2005), cucumbers (*Cucumis sativus* L.) (Hemming *et al*., 2008), and roses (Kempkes *et al*., 2012). However, to the best of our knowledge, there have been no studies to date on plant growth under roof-mounted PV modules that provide both fluctuating and relatively uniform light at the same daily light intensity.

In the present study, we hydroponically grew lettuce under roof-mounted PV modules during four seasons, which allowed 50 % overall light transmittance. Relatively uniform light irradiation was provided by a diffusion film under the roof-mounted PV modules, and the effects of different light conditions (direct but fluctuating and diffused but uniform irradiations) on the morphology, yield, and photosynthesis of lettuce were investigated.

2. Materials and methods

2.1 Solar greenhouse for the experiment

A solar photovoltaic (PV) module (156 mm × 156 mm) made of single-crystal silicon was used in the present study. Eighty-one PV modules arranged in a checkerboard pattern were sandwiched between two transparent glass boards (5 mm thickness each), which allowed 50 % overall light transmittance. The PV board (2 m × 2 m) inclined at 30°S (Fig. 1) was used as the roof of a small greenhouse, and the sides of the greenhouse were covered with a thin net (S-2000; Dio Chemicals, Ltd., Japan). In the winter season, the net was covered with a transparent PVC film (FTEP4936; Achilles, Japan) to increase the temperature inside the greenhouse. The greenhouses were located at lat. 34°59′ N. and long. 138°26′ E.

Two greenhouses equipped with this type of PV boards were prepared for the experiment, and another greenhouse equipped with a transparent glass board without PV modules was used as the control. A transparent light diffusing film (F-clean diffused; AGC Green-Tech Co., Ltd., Japan) was installed in one of the PV greenhouses just below the solar board to allow the diffusion of incident light (hereafter referred to as PV-D treatment). The other PV greenhouse transmitted incident light directly through the transparent glass between the PV modules (hereafter referred to as PV-T treatment).

The total power generation capacity of the two PV boards was 0.55 kW. The power generated by the PV modules during the experiments will be presented in another paper, and therefore only the monthly power generation is given here. The value in August, October, and December was 38.1, 30.0, and 24.3 kWh, respectively.

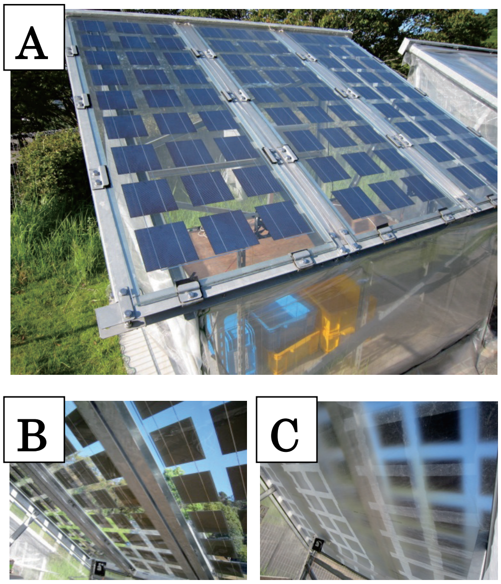

Fig. 1. Small experimental greenhouses with roof-mounted PV modules.
A: Greenhouse in PV-T treatment; B: Inside view of the PV board in PV-T treatment; C: Inside view of the PV board in PV-D treatment (a transparent light diffusion film was expanded just below the PV board).

2.2 Plant materials

Three to four lettuce (*Lactuca sativa* L. cv. Santa Clara) seeds were sown in individual urethane cubes (W24 mm × D24 mm × H28 mm). After germination, they were placed under three-band fluorescent lamps (40W, FLR40S, Panasonic, Japan) in a laboratory and grown in half-strength Otsuka-A nutrient solution (Otsuka Chemicals Co., Ltd, Japan) containing the major nutrients N, P, K, Ca, and Mg at 130, 60, 203, 115, and 30 mg L^{-1} concentration, respectively. They were irradiated for 18 h per day at 150 μmol m^{-2} s^{-1} photosynthetic photon flux density (PPFD). Air temperature was maintained at 22 ± 2 ℃. They were thinned to one seedling per cube 5 days after sowing and used for experiments 12 days after sowing.

2.3 Cultivation

Lettuce seedlings were grown in a deep flow technique（DFT）hydroponics culture system in which bubbles were produced by aquarium aeration stones. The nutrient solution used was a half-strength Otsuka-A nutrient solution. Temperature and humidity were not controlled in the experimental greenhouses.

Twenty-four cubes were individually inserted into holes made on two polystyrene foam plates（310 mm × 400 mm, 10 mm thickness）floating in the nutrient solution. The culture beds were installed at a height of 1 m, which was 30 cm below the lower part of the inclined PV board. The beds were located in the center in the greenhouses to reduce border effect. This position allowed the cultivated plants to receive sunlight through the roof for at least 2/3rds of the photoperiod throughout the four cultivation experiments. The cultivation experiments were conducted four times in the year and were initiated on May 16, August 10, September 19, and December 13. The dates of harvest are shown in Table 1. The nutrient solution was replaced after the first harvest of 12 seedlings. Fresh and dry weights of shoots, leaf length（LL）, leaf width（LW）, and leaf area of fully expanded leaves were measured after the first and second harvests. Relative chlorophyll content was estimated using a SPAD chlorophyll meter（SPAD-502 plus; Konica Minolta, Japan）. At the first harvest, fresh and dry weights of shoots and SPAD values were measured.

2.4 Environmental measurements

Water temperature in the nutrient solution tank and air temperature were measured with T-type thin thermocouples. Photosynthetic photon flux density（PPFD）was determined with four pyranometers（S-1-5; Taiyo Keiki Co., Ltd., Japan）. Three pyranometers were used for PPFD measurements in the greenhouses and fixed at 10 cm above the culture beds, and the remaining one was used to obtain the outside PPFD measurement and was fixed at 5 m from the nearest greenhouse. The pyranometers were individually calibrated in advance with a quantum sensor（LI-190, Li-Cor, USA）. PPFD measurements in the greenhouses was recorded every 1 min by a data logger unit（CR10X-AM416; Campbell Scientific, USA）throughout the experiments. Radiation power spectral distribution was measured with a portable spectrometer（JAZ-ULM-200; Ocean Optics, USA）on 5 clear days during the period from May to September. In the PV greenhouse, the electric power generated by the PV board was stored in three batteries and recorded by the data logger. The power generated by the PV board was used for the continuous operation of the data logger.

2.5 Photosynthetic measurement

Light-response curves of the net photosynthetic rate of lettuce leaves were obtained with a portable photosynthetic measurement system（Li-6400; Li-Cor, USA）. Measurements were made on fully expanded leaves of three to four lettuce plants in each treatment, one to two days before the second harvest in the first, second, and fourth cultivation experiments.

Initially, the leaf was acclimated to high light intensity（500 μmol m^{-2} s^{-1}）for 20 min to complete photosynthetic induction（Pearcy *et al.*, 1996）. PPFD was then increased to 1000 μmol m^{-2} s^{-1} and the automatic measurement was performed. Air temperature in the leaf cuvette was maintained at 25 ℃ in the spring and summer experiments and at 20 ℃ in the winter experiment. Relative humidity and CO_2 concentration were maintained at 60−80 % and 380 ppm, respectively.

Apparent dark respiration（R_d）, apparent quantum yield（ϕ）, curvature degree（θ）, and maximal rate of photosynthesis（P_{max}）were determined using the equation given below:

$$P_n = \frac{I \times \phi + P_{\max} - \sqrt{(I \times \phi + P_{max})^2 - 4 \times \theta \times I \times \phi \times P_{max}}}{2 \times \theta} - R_d$$

where P_n is the net photosynthetic rate and I is photosynthetic photon flux density（PPFD）（Soares-

Table 1. Date of sowing seeds, transplanting and harvests.

Season	Sowing	Transplanting	1st harvest	2nd harvest
Spring	May 7	May 16	May 25（9）	June 7（22）
Summer	August 1	August 10	August 20（10）	August 31（21）
Fall	September 10	September 19	September 28（9）	October 9（21）
Winter	November 16	November 26	December 7（9）	December 26（28）

Numbers in parentheses indicate days after transplanting.

Cordeiro *et al*., 2011）.

2.6 Quality analysis

2.6.1 Ascorbic acid content

Total ascorbic acid content was measured using the hydrazine method（Tadokoro *et al*., 2000）. Four grams of fully expanded leaf sample was mixed with 4 mL of cold 10 % metaphosphoric acid and ground mechanically. Thirty-two milliliters of metaphosphoric acid（5 %）was added to make the volume up to 40 mL. This solution was then filtered through a filter paper（Whatman No. 1, 7 cm diameter）and aliquots of the filtrate（2 mL）were transferred to test tubes. The total ascorbic acid（TAA）content was determined by reducing dehydro-ascorbic acid（DHA）to ascorbic acid（AA）with the addition of 0.2 mL indophenol（0.2 %）. To this mixture, 2 mL of a solution containing 2 % tin（II）chloride, 5 % metaphosphoric acid, and 1 mL of 2 % 2,4-dinitrophenyl hydrazine were added. This mixture was incubated at 37 ℃ for 3 h to obtain a permanent pink color. After incubation, 4.8 mL of 85 % sulfuric acid was added to make the volume up to 10 mL.

2.6.2 Questionnaire

To assess the quality attributes of lettuce, 17 university students and staff members were asked to fill in a questionnaire rated on a 5-point scale. The parameters assessed included degree of tenderness（hard = 1, soft = 5）, bitter taste intensity（non-bitter = 1, bitter = 5）, and overall acceptance（unfavorable = 1, favorable = 5）.

2.7 Statistical analysis

Statistical analysis was conducted using the Excel Statistics 2012 program for Windows（SSRI Co., Japan）to determine the significance of the effects of the shading treatments on plant growth, morphology, quality, and net photosynthetic rate.

3. Result

3.1 Environmental parameters

Typical diurnal change in PPFD on a sunny day is shown in Figure 2. PPFD in the control treatment showed a pattern similar to that measured outside, except for a sudden drop in PPFD in the morning（at 09:00 h）and afternoon（at 14:00 h）. The low PPFD was caused by the shade of the greenhouse frame. PPFD in the PV-T treatment showed frequent fluctuations caused by the direct light transmitted through the transparent glass. During the period when the sensor was shaded by the PV modules, the PPFD was ~100 μmol m^{-2} s^{-1}. PPFD in the PV-D treatment showed slight increase and decrease, and the value was measured as >200 μmol m^{-2} s^{-1} during the period when PPFD in the PV-T treatment was ~100 μmol m^{-2} s^{-1}.

The mean daily cumulative PPFD was highest in

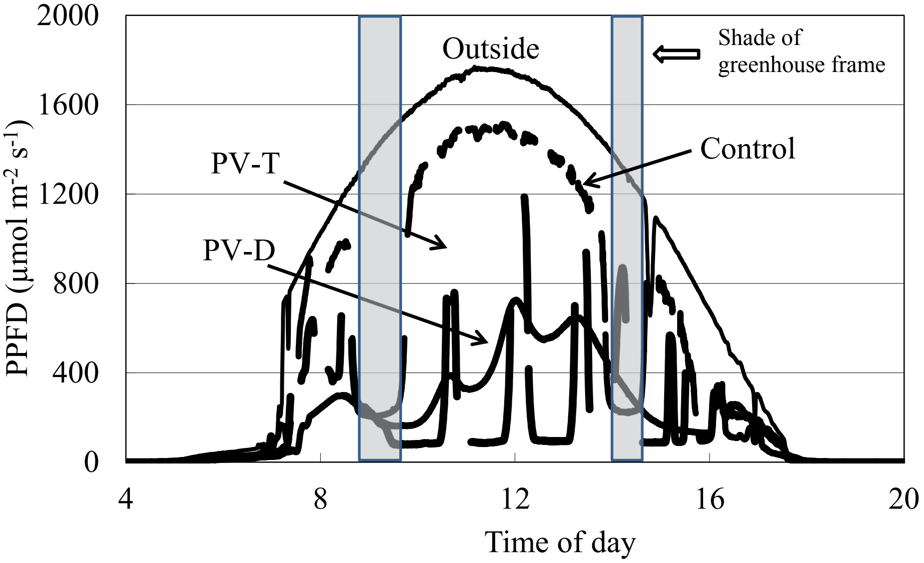

Fig. 2. Diurnal change in PPFD in the experimental greenhouses on a typical sunny day. The measurement was conducted on 4th Sep. 2012.

Table 2. Daily cumulative PPFD and daytime and nighttime temperatures of air and nutrient solution.

Season	Cumulative PPFD ($\mathrm{mol\ m^{-2}\ d^{-1}}$)			Daytime air temperature (℃)			Nighttime air temperature (℃)			Daytime nutrient solution temperature (℃)			Nighttime nutrient solution temperature (℃)		
	Control	PV-T	PV-D	Control	PV-T	PV-D	Control	PV-T	PV-D	Control	PV-T	PV-D	Control	PV-T	PV-D
Spring	19.8	9.5	8.9	31.2	30.1	29.6	21.2	21.3	20.9	26.6	24.9	24.9	20.2	21.5	20.5
Summer	23.9	9.3	9.8	32.4	31.9	31.6	25.7	25.9	25.4	33.7	31.2	31.3	30.9	29.9	30.4
Fall	17.5	7.7	8.1	28.9	27.4	27.4	23.5	22.6	22.4	28.5	26.0	26.6	26.0	24.3	25.1
Winter	10.6	3.8	3.9	13.8	13.7	13.6	11.1	11.0	10.9	14.5	14.0	14.0	12.8	12.3	12.3

Values were averaged over each cultivation period.

summer and lowest in winter (Table 2). The PPFD values in the PV-T and PV-D treatments were similar and were 36–48 % of that in the control treatment during all four seasons.

Shaded and transmitted sunlight in the PV-T treatment showed different spectral distributions (Figure 3). The ratio of blue to red light (B/R) was 0.56 in the transmitted sunlight but was 0.93 in the shaded sunlight. The ratio of red to far-red light (R/FR) was similar for the shaded and transmitted sunlight. The R/FR of diffused sunlight did not differ from that in the transmitted and shaded lights in the PV-T treatment. The spectral distribution of incident light in the control treatment was the same as that of the transmitted light in the PV-T treatment (data not shown). The measurements were conducted on 5 clear days, and similar results were observed. The ratio of diffused light to irradiation was also measured on several clear days. It was 60–70 % in PV-D but~10 % in both control and transmitted light in PV-T.

Daytime and nighttime air temperatures were highest in the summer season and lowest in the winter season (Table 2). Differences in the daytime air temperature between treatments were < 0.8 ℃ in the summer and winter seasons and larger (< 1.6 ℃) in the spring and fall seasons. Differences in the nighttime air temperature between treatments were < 1.6 ℃ in the four seasons. Daytime and nighttime nutrient solution temperatures ranged from 14.0 ℃ to 33.7 ℃ and from 12.3 ℃ to 30.9 ℃, respectively, with the highest values during summer and the lowest values during winter. The temperatures of the nutrient solution were 0.6–2.6 ℃ lower in PV-T and PV-D treatments than in the control treatment.

3.2 Lettuce growth

The dry weight of lettuce was significantly lower in

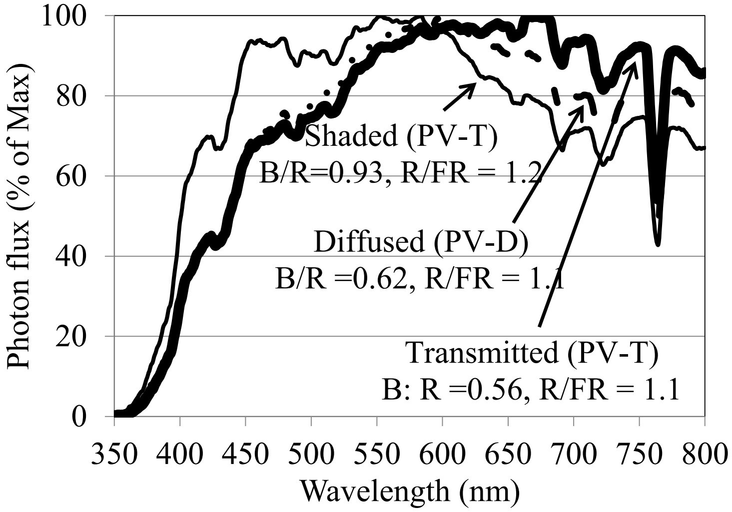

Fig. 3. Spectral distribution of shaded and transmitted sun lights in PV-T treatment and of diffused light in PV-D treatment.

The measurement was conducted at 11-12 AM on 4th Sep. 2012.

the PV-T treatment than in the control in most cases（Table 3）. In the second harvest of spring and winter cultivations, the dry weight in the PV-D treatment was significantly lower than in the control, but in summer and fall cultivations, it was comparable to the control. Compared to the PV-T treatment, the dry weight in the PV-D treatment was significantly higher in summer and fall.

RGR was lowest in the PV-T treatment, and RGR in the PV-D treatment was not significantly different from that in the control in the spring, summer, and fall cultivations.

Leaf area in PV-D was highest in the spring, summer, and fall cultivations, followed by PV-T and the control. Plant growth was delayed in winter, and the leaf area in the three treatments was much smaller in winter than in the other seasons.

The ratio of leaf length to leaf width（LL/LW）was highest in the PV-T treatment in all the four cultivations, followed by the PV-D treatment.

Specific leaf weight（SLW）was highest in the control in all four cultivations. SLW was not significantly different between the PV-T and PV-D treatments in spring, summer, and winter cultivations.

Table 3. Dry weight, RGR, single leaf area, leaf number, LL/LW, SLW and SPAD value of lettuce at the 1st and 2nd harvests.

Season	Treatment	Dry weight (g)	RGR ^{A}	Single leaf area（cm^2）^{B}	LL/LW ^{C}	SLW ^{D}（mg cm^{-2}）	SPAD value	Ascorbic acid content（mg/100 gFW）
Spring（1st harvest）	Control	0.22 a	0.29 a				33 a	
	PV-T	0.19 a	0.27 a				27 b	
	PV-D	0.21 a	0.29 a				26 b	
Spring（2st harvest）	Control	2.5 a	0.23 a	93 b	1.5 b	2.4 a	31 a	16.7 a
	PV-T	1.7 b	0.21 a	92 b	1.7 a	2.0 ab	27 b	15.5 b
	PV-D	1.9 b	0.22 a	102 a	1.7 ab	1.8 b	27 b	13.6 c
Summer（1st harvest）	Control	1.1 a	0.45 a				33 a	
	PV-T	0.74 b	0.41 b				27 c	
	PV-D	0.83 b	0.42 ab				29 b	
Summer（2st harvest）	Control	3.2 ab	0.24 ab	83 b	1.5 b	3.3 a	32 a	
	PV-T	2.8 b	0.23 b	103 a	1.8 a	2.2 b	27 b	
	PV-D	3.6 a	0.25 a	110 a	1.5 b	2.5 b	30 a	
Fall（1st harvest）	Control	0.12 a	0.23 a				25 a	
	PV-T	0.09 b	0.20 b				21 b	
	PV-D	0.12 a	0.23 a				24 a	
Fall（2st harvest）	Control	2.0 ab	0.22 ab	91 b	1.4 b	1.8 a	29 a	15.6 a
	PV-T	1.5 b	0.21 b	108 ab	1.7 a	1.3 b	25 b	14.9 b
	PV-D	2.2 a	0.22a	124 a	1.5 b	1.8 a	26 ab	14.4 b
Winter（1st harvest）	Control	0.05 a	0.1 a				27 a	
	PV-T	0.03 b	0.06 b				24 b	
	PV-D	0.03 ab	0.08 ab				26 ab	
Winter（2st harvest）	Control	0.55 a	0.13 a	20 a	1.3 b	3.7 a	34 a	12.7 a
	PV-T	0.28 b	0.11 b	15 a	1.5 a	2.6 b	29 b	11.8 b
	PV-D	0.34 b	0.12 ab	17 a	1.4 a	2.7 b	29 b	11.4 b

A: RGR at the 2nd harvest was calculated for the period between transplanting and the 2nd harvest.

B: Leaf area was determined for five fully expanded leaves.

C: LL and LW mean leaf length and width, respectively.

D: Specific leaf weight

Different letters indicate significant difference by Tukey test at 5 %.

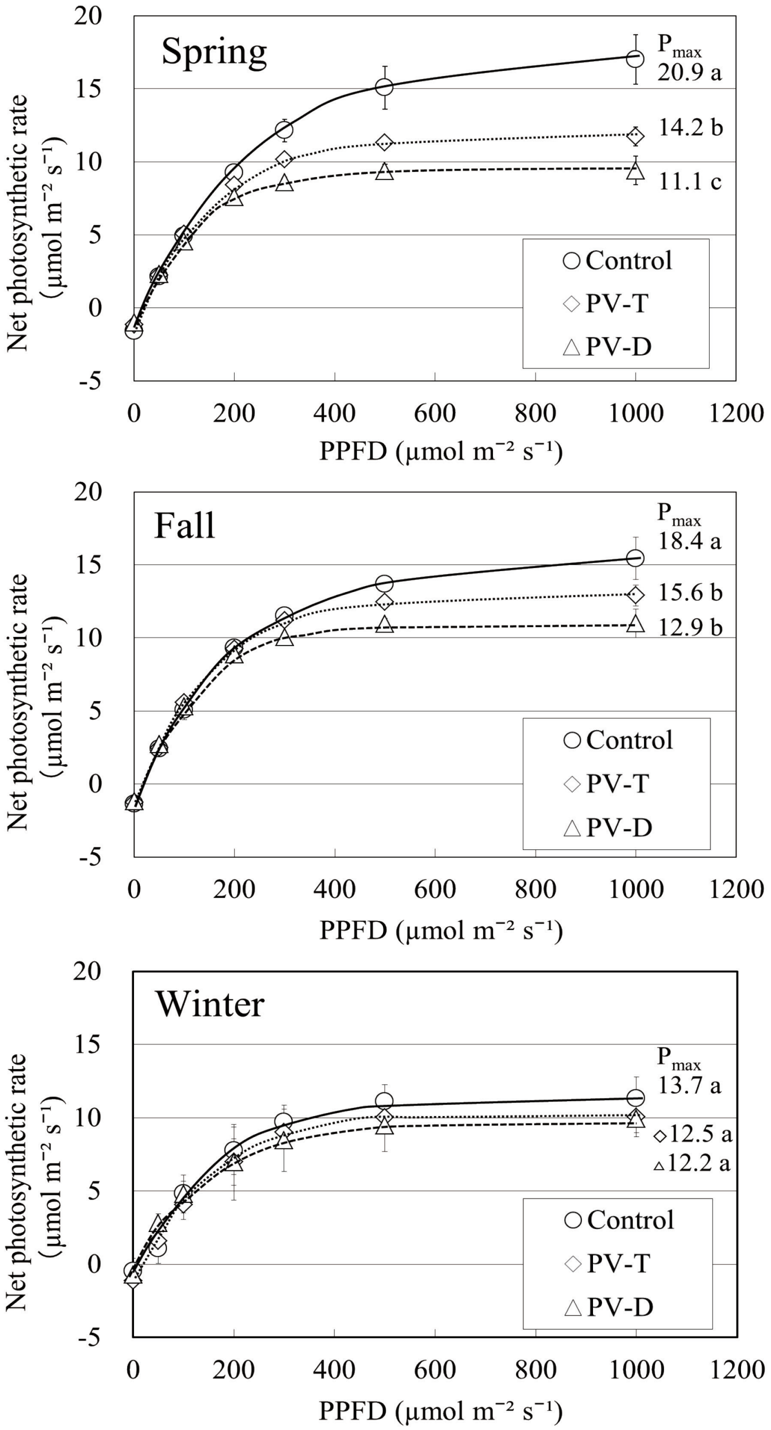

Fig. 4. Net photosynthetic rate of lettuce hydroponically grown under the roof-mounted PV modules.（n=3-4）
P_{max}: maximal rate of photosynthesis.
Different letters indicate significant difference by Tukey test at 5 %.

The SPAD value was highest in the control in all four cultivations. No significant differences were found in SPAD values between PV-T and PV-D in spring, fall, and winter cultivations.

3.3 Net photosynthetic rate

The net photosynthetic rate (P_n) of fully expanded leaves of lettuce tended to be higher in the control than in the PV-T and PV-D treatments (Fig. 4). In the spring and fall cultivations, the maximum potential photosynthetic rate (P_{max}) was significantly higher in the control ($p < 0.01$), followed by the PV-T treatment. P_n in the PV-D treatment tended to be lower than that in the PV-T treatment in spring, fall, and winter cultivations, and P_{max} was significantly lower in the PV-D treatment than in the control in the spring and fall cultivations ($p < 0.01$). In the winter cultivation, there was no significant difference in P_{max} between the three treatments. Values of R_d, ϕ, and θ were not significantly different between the three treatments (data not shown).

3.4 Food analysis

The ascorbic acid content in lettuce leaves was highest in the control in all three cultivations (Table 3). The PV-D treatment showed the lowest values.

The scores for tenderness of lettuce leaves were 3.1, 2.9, and 3.2 in the control, PV-T, and PV-D treatments, respectively (data not shown). However, the relative standard deviation of the score was 25−30 %, and no significant differences were observed between treatments. The scores for bitter taste intensity of lettuce leaves were 2.6, 2.7, and 2.3 in the control, PV-T, and PV-D treatments, respectively, and there were no significant differences between treatments. The scores for overall acceptance were significantly higher in PV-D (3.6), followed by PV-T (3.0) and the control (2.5).

4. Discussion

4.1 Comparison of plant growth and morphology between full-sun and fluctuating light conditions

In the PV-T treatment, the frequent fluctuations in PPFD were caused by the direct light transmitted through the transparent glass and shade under the PV modules. To the best of our knowledge, only two reports have been published on plant growth under roof-mounted solar panel modules causing fluctuating light conditions (Kadowaki *et al*., 2012; Marrou *et al*., 2013). However, there are some other reports on crops and pastures under sunfleck conditions that have considered the effects of fluctuating light on plant morphology and dry matter production (Peri *et al*., 2007; Varella *et al*., 2011). Hereafter, this effect will be considered by citing previous studies shown in these papers in addition to the two plant growth studies under roof-mounted solar panel modules.

Marrou *et al*. (2013) grew lettuce in fluctuating light conditions under densely arranged PV modules (30 % and 50 % of PV cover ratio) and observed that the specific leaf area (SLA) was significantly higher in these conditions, indicating that the leaf became thinner under fluctuating shade conditions. Similar to this result, SLW, which is the reciprocal of SLA, was lower in the fluctuating light conditions (PV-T treatment) than in the control (full sunlight) in our experiments, indicating that thinner leaves were produced under fluctuating light conditions.

In the present study, lower SLW in the PV-T treatment was accompanied by either or both larger leaf area (summer and fall) and higher LL/LW (all seasons). High LL/LW is consistent with a report on orchardgrass leaves that were narrower under fluctuating light conditions than under full-sun conditions (Peri *et al*., 2007). Varella *et al*. (2011) reported that stem height and internode length of alfalfa (*Medicago sativa* L.) were higher under fluctuating light conditions than under full-sun conditions. However, the values under constant shade conditions, in which daily PPFD was almost the same as that in the fluctuating light conditions, were the same as those under the full-sun conditions. These morphological changes during growth appear to be a type of shade avoidance response or succulent growth.

There are no studies on spectral distribution in fluctuating light conditions under roof-mounted solar panels. In the present study, the spectral distribution had different patterns between treatments (Fig. 3). However, R/FR ratio was not different between the control and PV-T treatments, indicating that this succulent growth was not caused by a decreased R/FR ratio, which has been reported to result in a typical shade avoidance response (*e.g*., stem elongation) (*e.g*. Casal and Smith, 1989, van Hinsberg and van Tienderen, 1997). A lower B/R ratio may cause high LL/LW in lettuce (Li and Kubota, 2009). However, the B/R ratio was higher under shade conditions in the PV-T treatment than under transmitted light conditions in the PV-T treatment and control, suggesting no involvement of the B/R ratio in the narrower leaves of lettuce. As a result, the fluctuating light with very low PPFD（~100 μmol m^{-2} s^{-1}.）in shade, independent of the spectral distribution, might be the cause of the succulent growth in lettuce.

The dry weight and RGR of lettuce were lower in the PV-T treatment than in the control. This was probably caused mainly by lower daily cumulative PPFD and partly by slightly lower daytime air temperature in PV-T（Table 2）. Similar results have been reported for *A. fistulosum*. L（Kadowaki *et al*., 2012）and field-grown lettuce（Marrou *et al*., 2013）under PV modules covering 13 % and 50 %, respectively, of the land area.

4.2 Effect of light diffusion films on plant growth and morphology

The application of light diffusion films in the PV-D treatment was shown to improve plant shape. Lettuce leaves became wider in the PV-D treatment than in the PV-T treatment, and LL/LW was not significantly different between the PV-D treatment and the control in spring, summer, and fall cultivations. Leaf area in PV-D tended to be large compared to PV-T; however, a significant difference was seen only in the spring cultivation. Dry weight and RGR were also higher in PV-D than in PV-T in summer and fall cultivations.

The application of light diffusion films or glass to normal greenhouses has been reported to improve plant growth. Chun *et al*.（2005）reported that fruit setting and yield of green pepper（*C. annuum*）under a light diffusion film were higher by 10.9 % and 12 %, respectively, than fruit setting and yield of green pepper under a polyethylene film. Hemming *et al*.（2008）reported that the yield of cucumber（*C. sativus* L.）increased in a greenhouse covered with a diffusion film. They observed that diffused light penetrated into the middle layers of these tall crops, resulting in a better horizontal light distribution in the greenhouse and enhanced plant growth. They also reported increased leaf area in the plants but did not mention the parameter LL/LW. Similar observations were reported by Kempkes *et al*.（2012）for rose（*Rosa hybrida*）and by Dueck *et al*.（2012）for tomato plants. These studies dealt with tall crops.

It has not been reported that wider leaves, resulting in improved lettuce appearance as a marketable product, are formed under diffused light conditions compared to fluctuating light conditions. As shown in Fig. 3, the light spectrum is not markedly different between diffused and transmitted light. For lettuce under diffused light conditions, the diffused light reaches the lower leaves of lettuce from the side, resulting in a larger amount of overall light absorption by the whole plant compared to fluctuating light conditions. It is reasonable that there is no increase in leaf length of lettuce plants in such light conditions in order to avoid the shade for receiving larger amounts of light. However, the physiological mechanism of the adaptation, such as wider leaf development, to diffused light is unclear.

4.3 Effect of light regime on lettuce quality and photosynthesis

The ascorbic acid content of lettuce was lowest in PV-D, followed by PV-T, in spring, fall, and winter. However, the differences between the three treatments were small, and the values were within the range shown in the Standard Tables of Food Composition in Japan（Ministry of Education, Culture, Sports, Science and Technology, 2010）. The questionnaire results suggest that the diffused light in PV-D may make the lettuce leaves softer and less bitter. The bitterness of lettuce leaves is known to be caused by a high nitrate content（Behr and Wiebe, 1992）, but the content was not measured in the present study. The score for overall acceptance was highest in PV-D, suggesting that customers favor softer and less bitter leaves produced under diffused light.

The P_{max} of lettuce was highest in the control among treatments, with the highest value in summer and the lowest value in winter. The value of P_{max} was higher in PV-T than in PV-D in spring, summer, and fall cultivations. To the best of our knowledge, there are no reports on the net photosynthetic rate of crops grown under fluctuating light conditions caused by PV modules; however, some reports are available on the photosynthesis of plants grown under fluctuating light conditions in a growth chamber or by artificial structures other than PV modules（Peri *et al*., 2007; Varella *et al*., 2011）.

The values of the P_{max} of orchardgrass（Peri *et al*., 2007）and alfalfa（Varella *et al*., 2011）grown under fluctuating light regimes were lower than those grown in sunlight. This low P_{max} was accompanied by thinner leaves（high SLA）, suggesting that the lower abundance of mesophyll cells is a factor regulating photosynthesis. In our study, lettuce in PV-T showed similar traits, *i.e*., lower P_{max}, high SLA（low SLW）, and low chlorophyll contents (low SPAD value), compared to the control.

There have been no reports, except for the study by Varella *et al.* (2011), that have compared the photosynthesis of plants grown under fluctuating and constant light conditions at the same daily PPFD level. They grew alfalfa under full-sun, fluctuating shade, and constant shade conditions and found that P_n measured was lowest in most cases under the constant shade facilitated by cloth. Although a common shade cloth was used in their shaded treatments and less diffused light was included compared to our study, their findings are consistent with our results. In our study, the lowest P_{max} value was accompanied in most cases by expanded leaves and low chlorophyll content (low SPAD value). Less abundant mesophyll cells might partly result in the lowest P_{max} value.

The initial slope of P_n against PPFD below 400 μmol m^{-2} s^{-1} was steep (Fig. 4), suggesting that a small difference in PPFD in the range results in a large difference in P_n. In PV-D, the plants continuously received a moderate intensity (200–400 μmol m^{-2} s^{-1}) of diffused sun light on clear days, but plants in PV-T received low PPFD < 100 μmol m^{-2} s^{-1} for more than 50 % of daytime (Fig. 2). This fact may result in a larger amount of carbon assimilated during daytime in the plants in PV-D than in PV-T.

In addition, as mentioned in section 4.2, diffused light may have a positive effect on photosynthesis in leaves at the lower position. Although the upper expanded leaves in PV-D have the lowest P_{max} between treatments, the total amount of carbon assimilated by a whole plant may be higher in diffused light than in fluctuating light (Farquhar and Roderick, 2003; Gu *et al.*, 2003).

4.4 Challenges for the use of roof-mounted solar panels in greenhouses

Ever since the application of PV modules to agriculture land was proposed (Goetzberger and Zastrow, 1982), there has been a growing interest in the installation of PV module frames on greenhouse roofs (*e.g.* Yano *et al.*, 2007, Sonneveld *et al.*, 2010). Power generation by roof-mounted PV modules may provide additional income to farmers if the crop production is comparable to production in a normal greenhouse. In the present study, we have shown for the first time the possibility of improving lettuce growth by using light diffusion films under roof-mounted PV modules.

However, to obtain proper crop growth throughout the year, the shortage of light during winter may be problematic under PV modules. As shown in Table 2, the daily cumulative PPFD in winter was half of that in summer, and this low PPFD under PV modules, coupled with low temperatures, resulted in a lower RGR compared to the other three seasons (Table 3). Although the effect of heating of the nutrient solution on lettuce growth was not addressed in this study, temperature and irradiance may be key factors controlling lettuce growth. The lightweight PV film developed recently (*e.g.* Eberspacher *et al.*, 2001) is a potentially viable option for increasing crop productivity because it may be possible to change the position of the PV modules depending on the season. To acquire increased daily irradiance at the low sun angle during winter, the PV films can be temporarily moved to the north side of the roof on an east-oriented greenhouse to allow more light into the greenhouse. Even in this case, light diffusion films may play an important role in improving plant growth.

5. Conclusion

Fluctuating light conditions under roof-mounted PV modules reduced lettuce growth, *i.e.*, a lower dry weight and RGR with longer leaves. Diffused light conditions at the same daily PPFD improved lettuce growth. The leaves became wider and the ratio of leaf width to length was close to that in the control in spring, summer, and fall cultivations. Although the net photosynthetic rate of the fully expanded leaves of lettuce grown in diffused light was lowest, dry weight and RGR were comparable to the control in summer and fall cultivations. Diffused light might penetrate into the lower layers of the leaf canopy, resulting in an increased CO_2 fixation rate by the whole canopy. Our results suggest that the application of light diffusion films is a viable option for improving crop productivity under roof-mounted PV modules.

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