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Research Article

Efficiency Improvement of Ground-Mounted Solar Power Generation in Agrivoltaic System by Cultivation of Bok Choy (*Brassica rapa subsp. chinensis* L.) Under the Panels

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Abstract. An agrivoltaic system is a combination of solar power generation and crop production that has the potential to increase the value of land. The system was carried out at a 25-kW photovoltaic (PV) power plant located at the Asian Development College for Community Economy and Technology (adiCET), Chiang Mai Rajabhat University, Thailand. The growth and yield of bok choy (*Brassica rapa subsp. chinensis* L.) and the solar power output were investigated and compared with the control. Moreover, the efficiency of the agrivoltaic system was evaluated. The results indicated that the average intensity of solar radiation of 569 W/m^2 was obtained. The highest power generation was recorded in the PV with crop production of 2.28 kW. Furthermore, the control plot of crop production at 35 days provided higher growth than bok choy plots under solar panels of 2.1 cm in plant height, 6 in leaf number, 2.2 cm in leaf length and 0.2 cm in leaf wide. High-yield of bok choy was also obtained in the control plot of 17.31 kg. Although the yield of bok choy is extremely low, possibly because of light intensity, crop cultivation under solar panels could reduce the module temperature to less than the PV control of 0.18 °C, resulting in increased voltage and power generation by around 0.09 %. Therefore, an agrivoltaic system is another option for increasing revenue and land equivalent ratio in solar power plants focusing only on electricity generation. However, suitable crops for the space under PV panels should be investigated further.

Keywords: Agrivoltaic system, Ground-mounted solar power plants, Solar power generation, Solar power output, Bok choy.

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1. Introduction

Presently, solar energy can be converted into thermal or electrical energy. Solar energy is the cleanest and most abundant renewable energy source available at present, which can be converted into electricity directly by using photovoltaic (PV) systems (Missoum *et al.,* 2021). Such systems usually consist of photovoltaic modules, batteries, charge controllers, inverters, load controllers, circuit breakers and wiring (Wasfi 2011). In 2018, the global capacity of photovoltaic power plants was over 500 GW (Jäger-Waldau 2018), most of which comprised ground-mounted photovoltaic power plants with a capacity of 471 GW. Moreover, the remainder is separated by 27.9 GW of solar roof tops (Europe 2018) and 1.1 GW of solar floating (Gamarra *et al.* 2019).

The total land-use requirement for ground-mounted photovoltaic power plants was 1,448,612 Ha (Ong *et al.* 2013). In line with the global trend, ground-mounted photovoltaic power plants are still favored in Thailand. Solar power plant installations cover an area of approximately 9,020 ha, which can presently generate total solar power at 2,819 MW per day (Chimres *et al.* 2016). By 2036, the Thai government plans to increase the number of solar farms to generate increased capacity at more than 6,000 MW (Department of Renewable Energy Development and Energy Efficiency 2015). The expansion of solar power generation will inevitably require more land area, which may affect not only the land use competition, but also food security in the future. While solar power plants have been promoted in Thailand and other countries, the areas under the solar panels have not been fully utilized because they focus only on solar power generation. Therefore, a combination of solar power generation and food production to increase the land benefit, also known as an agrivoltaic system, has been studied for its potential advantages (Valle *et al.* 2017; Dupraz *et al.* 2011). In addition, annual income could be increased by using agrivoltaic systems (Li *et al.* 2017; Mohammadi *et al.*, 2017). Planting crops for agrivoltaic systems involves co-production between the solar power generation and crop production in a single space at the

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same time. Shade-tolerant plants have been suggested for planting under solar panels (Beck *et al*. 2012). A study by Malu *et al.* (2017) indicated that grape farms deploying the agrivoltaic systems may increase the economic value by more than 15 times compared to conventional farming. Moreover, Trypanagnostopoulos *et al.* (2017) found that the plant growing results under shading effect were satisfactory as they were at the same level with a reference greenhouse without a PV-covered roof.

There are presently 2 guidelines on employment of agrivoltaic systems which are land utilization under PV panels of fixed PV systems without agricultural plans and planned PV system installation with agricultural plans. It was found that fixed PV system installation for electricity generation as the only purpose was with the environment under PV panels that did not sufficiently suit cultivation. Hence, the number of these studies on land utilization under PV panels of PV systems are still very few studies. Consequently, in this work, the efficiency improvement of ground-mounted solar power generation through plant cultivation under solar panel were investigated.

2. Materials and Methods

2.1 Ground-mounted PV power plant

The study of the agrivoltaic system was carried out at a 25-kW PV power plant located at the Asian Development College for Community Economy and Technology (adiCET), Chiang Mai Rajabhat University, Thailand. This PV power plant was designed and installed in the purpose of generating electricity only. The plant consists of 5 PV arrays in a 25 kWp AC micro grid-connected PV system as shown in Figure 1. The system is connected to a distribution system in the Chiang Mai Rajabhat University grid. There are 225 amorphous PV modules installed at 2.0 and 0.8 m from the ground on the north and the south direction, respectively, with the total PV panels surface area of 352.15 m^2. The modules were installed with a solar charge controller, 40 deep-cycle batteries and a grid-interactive inverter. The system in order to distribute the power to Chiang Mai World Green City (CWGC), consisting of six households, an office, a restaurant, a coffee shop and a convenience store.

2.2 Crop plants

The condition under the AC micro grid-connected PV system is not suitable for general crop production, however shade-tolerant crops could grow. Therefore, Bok choy (*Brassica rapa subsp. chinensis* L.) was selected for investigated in this study. The reason was that it is a biennial plant that can grow best in partial shade or receive 3-5 h of sun light exposure each day (Chintu, 2021). Moreover, it can tolerate temperatures as high as 35°C and as low as -3°C and prefers slightly acidic (pH 5.5 to 7.0) sandy soil rich in nutrients (Liu *et al*. 2019). All plants at the control plot of the experiment were under direct sun light by around 10 h (07.00 a.m. – 05.00 p.m.) while the plants under solar panels by around 20 % were under direct sun light for 3 h in the morning (07.00 a.m. – 10.00 a.m.)

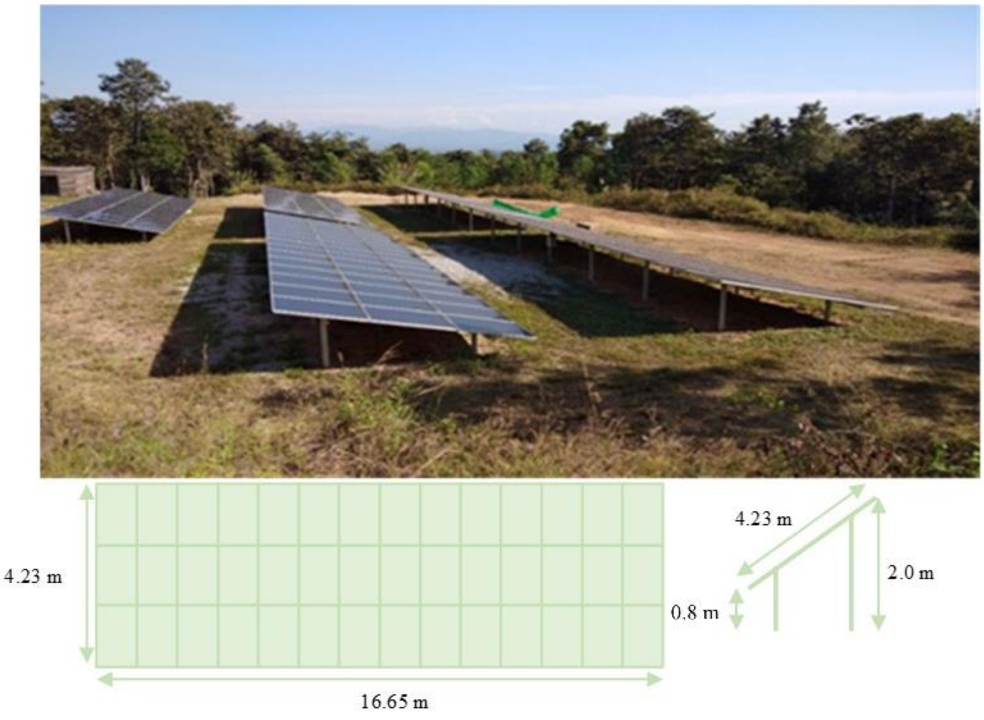

Fig. 1 25-kW AC PV farm at adiCET

2.3 Soil preparation for crop production under the PV panels

The structure of the soil under the solar panels is sandy loam mixed with rock and is of low nutrient value. Therefore, soil under solar panels was amended by organic matter. The soil under 4 PV panels and a control (outside the PV panels) was prepared and ploughed. From the photo in Figure 2, the plot should be way around 1 x 15 cm (15 m^2). Then, it was mixed with an organic compost (pork manure mixed with rice husk at a ratio of 7:3) of 100 kg per bed and released for 30 days. The nutrition of soil was analyzed with commercial soil test kit. Results indicated that soil had a slightly acidic pH of 6.2. Total nitrogen, phosphorus and potassium in soil were report to be 20, 20 and 400 ppm, respectively. After that, bok choy seedlings, 25 days after germination, were transplanted into each plot at 15 cm between the plants and rows, providing a density of 132 plants/plot. They were watered twice a day (07.00 a.m. and 05.00 p.m.) with 500 L of water per day.

2.4 Monitoring and evaluation

2.4.1 Environment and electricity

The solar radiation (08.00 a.m. – 05.00 p.m.), temperature of solar panels, voltage and the current were monitored and recorded during the same day of crop monitoring. Moreover, the surface area of the solar panels was also measured. Solar power generation was then evaluated and compared with control, as in Equation 1 (Ekpenyong *et al.* 2013).

$$Power\ generation\ (kW) = \frac{voltage\ (V) \times current\ (I)}{1000} \quad (1)$$

2.4.2 Vegetative growth and yield of crops

Various vegetative parameters including the height of plants, the number of leaves, the size of leaves and the weight of plants were monitored. The plant height was measured from the soil line to the shoot apex. Simultaneously, the leaf number per plant was counted followed by measuring the length and width of the leaves. All the various vegetative parameters were recorded every 7 days, starting from the 7th day after transplanting to the harvest date. At 35 days after transplanting, five plants per plot were harvested, weighed, and recorded. After that, they were dried at 60°C with a hot air dryer for 48 h or to constant weight.

Subsequently, the dry weight of samples was determined for percentage of biomass (Kongake *et al.* 2014), as in Equation 2. Finally, the total crop yield was also harvested and weighed.

The experimental data was statistically analyzed using Microsoft EXCEL. Analysis of Variance (ANOVA) was carried out on every measured parameter to determine the significance of differences between the means of each plot. Means for each parameter were separated by Duncan's Multiple Range Test (DMRT) at P ≤ 0.05 (Kongake *et al.* 2015).

$$Biomass\ percentage = \frac{dry\ weight}{fresh\ weight} \times 100 \quad (2)$$

3. Results and Discussion

3.1 Environment and electricity

The planting period was conducted from July10th to August 14th, 2018, which was a monitoring period for the solar radiation, temperature, voltage and current. Meanwhile, the surface area of the solar panels was measured from the top side of panels that faced to the sunlight.

3.1.1 Solar radiation

The solar radiation indicated that the average solar radiation intensity of 569 W/m^2 was obtained. From the graph in Figure 3, the highest intensity recorded is below 1,000 W/m^2 during daytime from 11.30 a.m. – 12.00 p.m.

3.1.2 Temperature

The temperature under the solar panels, including with the control, showed that their temperatures were higher than the ambient temperature as in Figure 4. However, the average temperature of all solar panels with crop production was lower than the control around by 0.18°C. The result was consistent with Barron-Gafford *et al.* (2019).

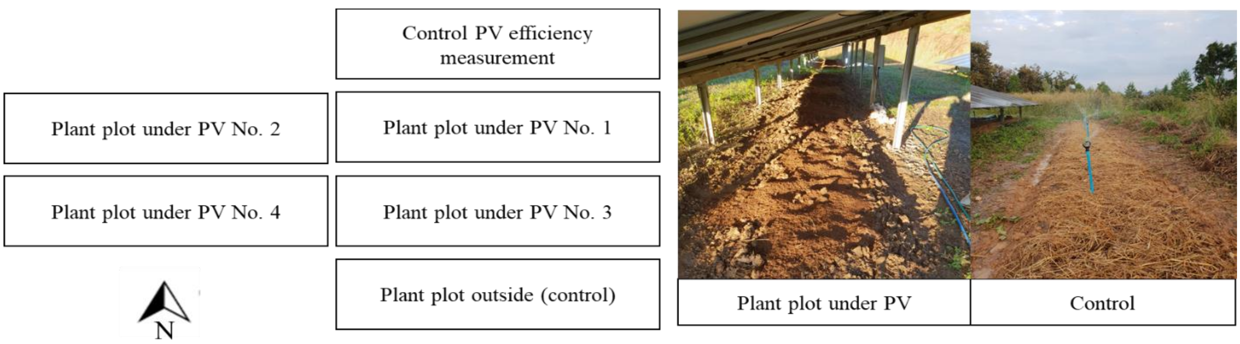

Fig. 2 Experimental layout and plots for crop production

3.1.3 Solar power generation

PV No.1 and 3 could generate power at around 2.28 and 2.12 kW, respectively, which was higher than the control. The control could generate power of approximately 2.06 kW, which was similar to PV No.2. The lowest power generation was recorded in PV No.4 (~1.87 kW), as in Figure 5.

The experimental design is not homogeneous since PV No. 4 was covered the shading from trees and a mound of dirt near the array after 03.00 p.m. Therefore, PV No.4 generated less electricity than the control. According to the suggestion of Sathyanarayana *et al*. (2015), the area of the shade had a significant effect on the I-V characteristics as well as power output.

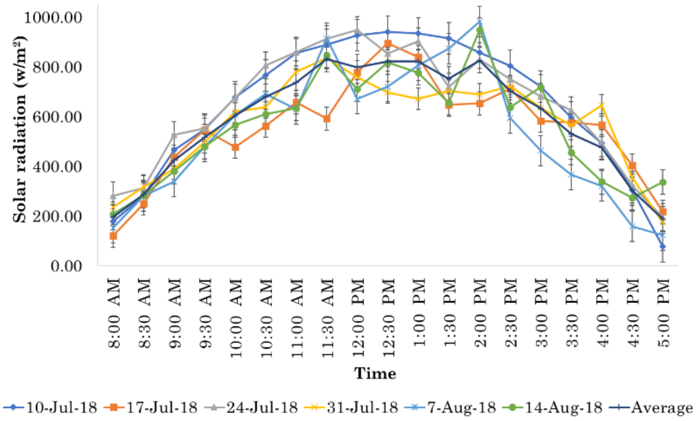

Fig. 3 Solar radiation intensities

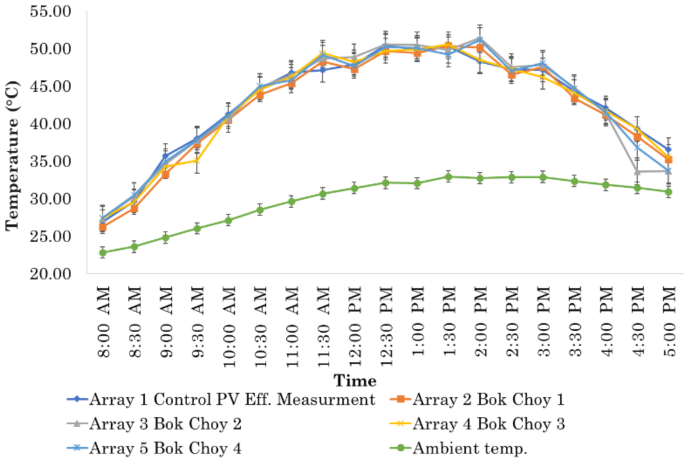

Fig. 4 Solar panel and ambient temperature

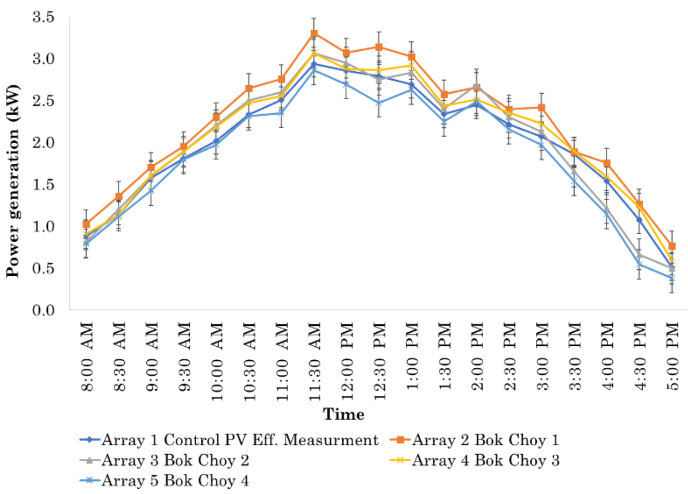

Fig. 5 Solar power generation

Table 1
Growth of plants

Days	Vegetative growth	Plot					F test	CV (%)
		1	2	3	4	Control		
7th	The height of plant (cm)	14.3a	13.1ab	12.4b	13.7ab	13.31b	*	6.8
	The leaf number	6	5	5	6	5	ns	11.7
	The left width (cm)	3.9a	3.5ab	3.3ab	3.7a	2.9b	*	15.2
	The leaf length (cm)	10.4a	9.3ab	8.7bc	9.0ab	7.2C	**	12.8
14th	The height of plant (cm)	16.7	16.1	15.4	16.2	16.8	ns	8.1
	The leaf number	8	7	8	8	9	ns	8.1
	The left width (cm)	4.4	3.9	4.3	4.7	5.0	ns	17.4
	The leaf length (cm)	12.1a	10.0b	11.3a	12.0a	11.5a	**	8.0
21st	The height of plant (cm)	18.7a	17.8ab	16.1b	17.4ab	19.3a	*	7.9
	The leaf number	9ab	8b	10a	9ab	10a	*	12.1
	The left width (cm)	4.6b	4.1b	4.8b	4.8b	5.8a	*	15.2
	The leaf length (cm)	13.2a	10.3b	11.7ab	12.7a	13.0a	**	9.2
28th	The height of plant (cm)	20.6	20.2	17.1	20.1	21.4	ns	13.6
	The leaf number	11b	10b	12ab	11ab	14a	*	13.6
	The left width (cm)	5.3b	4.4b	5.3b	5.4b	7.2a	**	19.1
	The leaf length (cm)	13.8ab	11.9b	12.1b	14.3ab	15.9a	*	14.1
35th	The height of plant (cm)	21.5	21.7	20.8	21.6	23.5	ns	10.7
	The leaf number	15b	11c	14bc	13bc	19a	**	15.7
	The left width (cm)	5.6b	4.8b	5.9ab	6.8ab	8.0a	*	24.1
	The leaf length (cm)	13.9b	12.3b	13.7b	14.5b	17.9a	**	14.5

Note: a, b and c-significantly different at $p \leq 0.05$ by Duncan's Multiple Range Test, *-significant at the 0.05 level, **-significant at the 0.01 level, ns-non significant, CV-coefficient of variation

3.2 Vegetative growth and yield

Similar to the date of monitoring and evaluation for environment and power generation, the height of plants, leaf number, leaf size and weight of plants were analyzed.

3.2.1 Height of plants

The mean height of bok choy plants was not influenced by the conditions under PV panels. The results as in Table 1. show that the average height of bok choy in the control plot after 14 days until harvesting was from 16.80 to 23.5 cm, respectively, which was not significant difference to all the crops in the plots under PV panels. Moreover, the stems of the bok choy under the solar panels were thin and smaller than the control plot as in Figure 6. The reason was that the bok choy planted under the solar panels received less light intensity. The result was consistent with the experiment by Nguyen *et al.* (2019), in which spinach (*Spinacia oleracea*) farming under lower light intensity resulted in a lower height than suitability.

3.2.2 Leaf numbers

The shading of the solar panels could reduce solar intensity of 1,200 µmol/m/s (Rittiram *et al.* 2019) for shining on the area under the solar panels at lower than 74 µmol/m/s, which was less than the requirement of bok choy by around 65 %. Consequently, the bok choy in the plot under PV panels gave lower leaf numbers than the control as shown in the results in Table 1. According to the results of Nguyen *et al.* (2019), the low leaf number of spinach plants was obtained under low light intensity.

3.2.3 Leaf sizes

The length and width of the leaves were found to be significantly influenced at 35 days. The longest and widest leaves were recorded in the control as in Table 1. It was observed that the size of the leaves in the control was larger than all bok choy plots under PV panels because the control received sufficient light intensity. The result was consistent with Petchthai *et al.* (2017), who studied the effect of light intensity and light-exposure duration on the growth and quality of lettuce. Their experiment found that high light intensity provided the size of the canopy wider and greater leaf size than the lower one.

3.2.4 Weight of plants

There was significant effect of different plots under PV panels and the control on fresh and dry weight of bok choy. Similar to the reasons above for vegetative parameters, the control provided the highest shoots and fresh root weight, shoots and root dry weight, and total fresh weight and dry weight as in Table 2. Moreover, the highest total yield per plot was recorded in the control, consistent with the experiment by Weiguo *et al.* (2012). They investigated the effects of different light intensities on anti-oxidative enzyme activity, quality and biomass in lettuce. The results showed that high light intensity could affect fresh weight better than low light intensity because the light intensity directly affected the rate of photosynthesis.

Fig. 6 Bok choy plot under solar panels and the control plot

Table 2
Fresh and dry weights of Bok Choy at harvest date

Plot No.	Fresh weight		Dry weight		Total		Total yield (kg)
	Shoots (g)	Roots (g)	Shoots (g)	Roots (g)	Shoots (g)	Roots (g)	
1	51.8b	5.6b	1.9b	0.4	57.3b	2.2b	2.31
2	26.7b	2.8b	5.6b	3.3	29.5b	8.8ab	1.05
3	49.0b	6.1b	2.4b	0.4	55.1b	2.9b	1.50
4	36.3b	3.8b	1.9b	0.4	40.1b	2.4b	1.16
Control	233.9a	23.3a	16.7a	2.82	257.2a	19.5a	17.31
F test	**	**	**	ns	**	*	
CV (%)	8.1	8.6	8.1	8.6	12.7	12.7	

Table 3
Efficiency of the agri-voltaic system

	Power generation (kW)	Crop yield (kg)
Control PV Eff measurement	2.06ab	-
PV No.1	2.28a	2.31
PV No.2	2.05ab	1.05
PV No.3	2.12ab	1.50
PV No. 4	1.87c	1.16
Control pot	-	17.31
F test	**	-
CV (%)	5.04	-

Table 4
Correlations between power generation and crop yield

Variables	Power generation (kW)	Crop yield (kg)
Power generation (kW)	1.000	0.850*
Crop yield (kg)	0.850*	1.000

Note: *-$p < 0.05$

3.3 Efficiency of the agrivoltaic system

The combination between PV power generation and crop production or agrivoltaic systems as in Table 3 indicated that the power generation were found to be significantly influenced. The highest power generation was recorded in PV No.1 compared to the control. The PV No.3 could generate power higher than the control but there was non-significant. The correlation of PV power generation and crop production was significant correlated as in Table 4 which the experimental result showed that the highest power generation was generated with the highest crop production under the PV panel. The result indicated that planting crops under the PV panels could reduce the temperature under the PV panels. On the other hand, the control could generate power similar to PV No.2 and was significantly higher than PV No.4 due to the geographical characteristic problem. Although the effect from light intensity caused reduced yield of bok choy under solar panels, steam caused by evaporation of water from the soil surface and by transpiration of plant under the solar panels could reduce module temperature. The decrease of PV panel temperature could promote the voltage and increase power generation by around 0.09 %, which was similar to the results of Boonsri *et al.* (2017), Peng *et al.* (2017) and Jatoi *et al.* (2021).

6. Conclusion

To the point, solar power generation with crop production could promote power generation, but the shading of solar panels interfered with crop production. Consequently, the use of agrivoltaic systems should be encouraged. Not only because the crop production under the PV panels could promote power generation, but crop cultivation under solar panels is another option to increase revenue and land equivalent ratio in solar power plants which designed and installed for generating electricity only. For solving the problems mentioned above, shade-tolerant crops will be considered for planting under the solar panels. They consist of leafy vegetables (lettuce, celery, spinach and spring onion), root and tuber vegetables (ginger, galangal, sweet potato and carrots) and solanaceous crop (chili). However, in assessing the physical properties of plants, root vegetable cultivation under solar panels can damage to the structure of ground-mounted photovoltaic power plants. Nevertheless, leafy vegetables and solanaceous crop as well as crop production conditions should be investigated further.

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