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Crop Cultivation Underneath Agro-Photovoltaic Systems and Its Effects on Crop Growth, Yield, and Photosynthetic Efficiency

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Abstract: Agro-photovoltaics (APV) could be the optimal means of sustainable development in agricultural areas once a few challenges are overcome, perhaps the greatest of which is the constant shading from AVP structures. This study examined how the growth and yield of rice, potato, sesame, and soybean crops could be optimized when grown underneath different APV systems. The solar radiation, shading levels, and temperatures during crop cultivation were measured. In addition, the photosynthetic efficiency was measured at different growth stages. Adjacent to the APV systems were the control plots with full sun. In these studies with potato crops grown under APV systems, most growth and yield parameters were similar to those grown in the control plot except for the plant height. On the other hand, sesame crops grown underneath the APV systems had a lower stem length, effective branching number, 1000 seed weight, and a reduced yield of 19% compared to the crops from the control plot. In two distant locations (Paju and Youngkwang), soybean crops grown underneath APV systems at both sites showed increased ungrained ratios per pod and a reduced yield of 18–20% compared to the control plot. Finally, rice crops cultivated underneath the APV systems had a lower panicle number per hill, spikelet number per panicle, 1000 seed weight, and yield reduction of 13–30% compared to the control plot. Overall, crops grown underneath the APV systems had a greater plant height and stem length. Moreover, the solar radiation and PAR underneath the APV systems were also lower than in the control plots. The photosynthetic efficacy in rice plants grown underneath the APV systems was lower than in the control plots. The photosynthetic efficacy may help lower the crop yield when cultivation is underneath an APV system.

Keywords: agro-photovoltaic; crop; photosynthesis; weather factor; yield

Citation: Lee, H.J.; Park, H.H.; Kim, Y.O.; Kuk, Y.I. Crop Cultivation Underneath Agro-Photovoltaic Systems and Its Effects on Crop Growth, Yield, and Photosynthetic Efficiency. *Agronomy* **2022**, *12*, 1842. https://doi.org/10.3390/agronomy12081842

Academic Editor: Xiangnan Li

Received: 7 July 2022
Accepted: 28 July 2022
Published: 4 August 2022

1. Introduction

Fossil fuels are heavily relied upon as energy sources and are still the largest source of greenhouse gas emissions in the power generation sector [1,2]. On the other hand, to comply with the Paris Agreement and meet its objective of limiting global warming, the demand for establishing an alternative energy supply in the world has led to the use of renewable energy, which has favorable mitigating effects on carbon dioxide with minimal environmental impact [3–5]. Common renewable energy sources include biomass, hydropower, geothermal, wind, and solar. Furthermore, the development of renewable energy sources for replacing fossil fuels has become one of the major societal challenges in solving the energy and climate change crisis.

Among the renewable energy technologies available, photovoltaic power generation requires a huge land area which can no longer be used for agricultural applications. Photovoltaic systems have been adapted to reduce their negative effects on agriculture. The concept of the agro-photovoltaic (APV) system was introduced by Goetzberger and Zastrow [6] more than three decades ago. Since then, APV systems have become an innovative facility to encompass photovoltaic power production and crops in the same agricultural fields [4]. The Korean government is implementing APV systems in rural areas as part of the "Renewable Energy 3020 Implementation Plan"and the "2050 Carbon Neutral Strategy". The Korean government aims to increase the target level from APVs to 10.0 GW by 2030 [7,8].

The solar energy generated from APV can have the following benefits: a more than 30% increase in the economic value of the land [9] if yield losses through shading effects are minimized by the selection of suitable crops, and a 60–70% increase in overall land productivity [4]. As integrated photovoltaic systems contribute to conciliate food security and green energy supply [10], an APV may be the optimal means of sustainable development in agricultural areas [11].

Nevertheless, the main challenge faced by these systems is that they still adversely affect crop productivity and quality because of the shading effects [12]. A decrease in solar radiation intercepted by the crops due to shading in APV systems can negatively affect crop production [13]. Thus, the effects of shading must be considered when exploring potential APV conditions [14,15].

The light quantity is a vital component of crop cultivation that links the photosynthetic rates and morphological processes of plants to their growth and development [15,16]. In previous studies, the yields of maize and potatoes were reduced under shading conditions when applied at growth stages in limited periods [17–19]. On the other hand, the AVP structure is shaded for all periods of crop cultivation [20,21]. For example, the potato tuber yield was decreased by 38.2% in crops grown under APV compared to the conventional potato tuber yield [22]. In a modified crop model adapted to the shading conditions underneath an APV, Homma et al. [23] reported that a 20% reduction in solar radiation led to a 20% reduction in rice yield. In another study, Marrou et al. [24] showed that light reduction had a significant impact on the final crop yield of spring and summer lettuces in APV.

Although APV technology is being applied worldwide, there is very little accompanying scientific research to examine its impacts on agronomic parameters, such as crop performance and crop yields. Thus, this study examined how the growth and yield of rice, potato, sesame, and soybean crops could be optimized when grown underneath different APV systems. The solar radiation, shading levels, and temperatures were measured during crop cultivation, and the photosynthetic efficiency was measured at different growth stages.

2. Materials and Methods

2.1. APV Research Facilities

This study was conducted across seven APV facilities across South Korea. Potato and sesame crops were planted at one facility each, whereas soybean and rice were planted at two and three APV facilities, respectively. The areas of APV facilities were 1980 m^2 for potato, 1815 m^2 for sesame, 1030–2800 m^2 for soybean, and 1180–3267 m^2 for rice. The areas of control plot for each crop were over 1000 m^2. The shading rates of the APV used in this study ranged from 25% to 32%. The panel height of the APV ranged from 4.0 to 4.5 m. The power generation of the APV ranged from 97 to 150 KW. The average total precipitation during the crop growing season, from March to October, at seven APV facilities ranged from 920 to 1600 mm. Table 1 and Figure 1 provide more detailed information on these APV structures.

Table 1. Agrophotovoltaic (APV) facilities used in this study.

Crop	APV Location	Latitude	Longitude	Power Generation (KW)	Shading Rate (%)	Panel Shape	Module
Potato	Cheongju	127°27′42″	36°41′55″	99	31.6	Individually distributed	36 cell, 3 × 12 type
Sesame	Goesan	127°38′10″	36°48′48″	99	31.6	Individually distributed	36 cell, 3 × 12 type
Soybean	Paju	126°56′33″	37°58′16″	150	32.0	Individually distributed	36 cell, 4 × 8 type
	Youngkwang	126°26′26″	35°24′38″	97	28.0	Holding type	72 cell ×4, 6 × 12 type
Rice	Seungju	127°24′36″	35°01′37″	100	25.0	Double axis tracing	119 cell, 7 × 17 type
	Naju	126°49′31″	35°01′44″	107	32.0	Stationary type	72 cell, 6 × 12 type
	Boseong	127°02′55″	34°44′14″	99	31.6	Stationary type	36 cell, 12 × 3 type

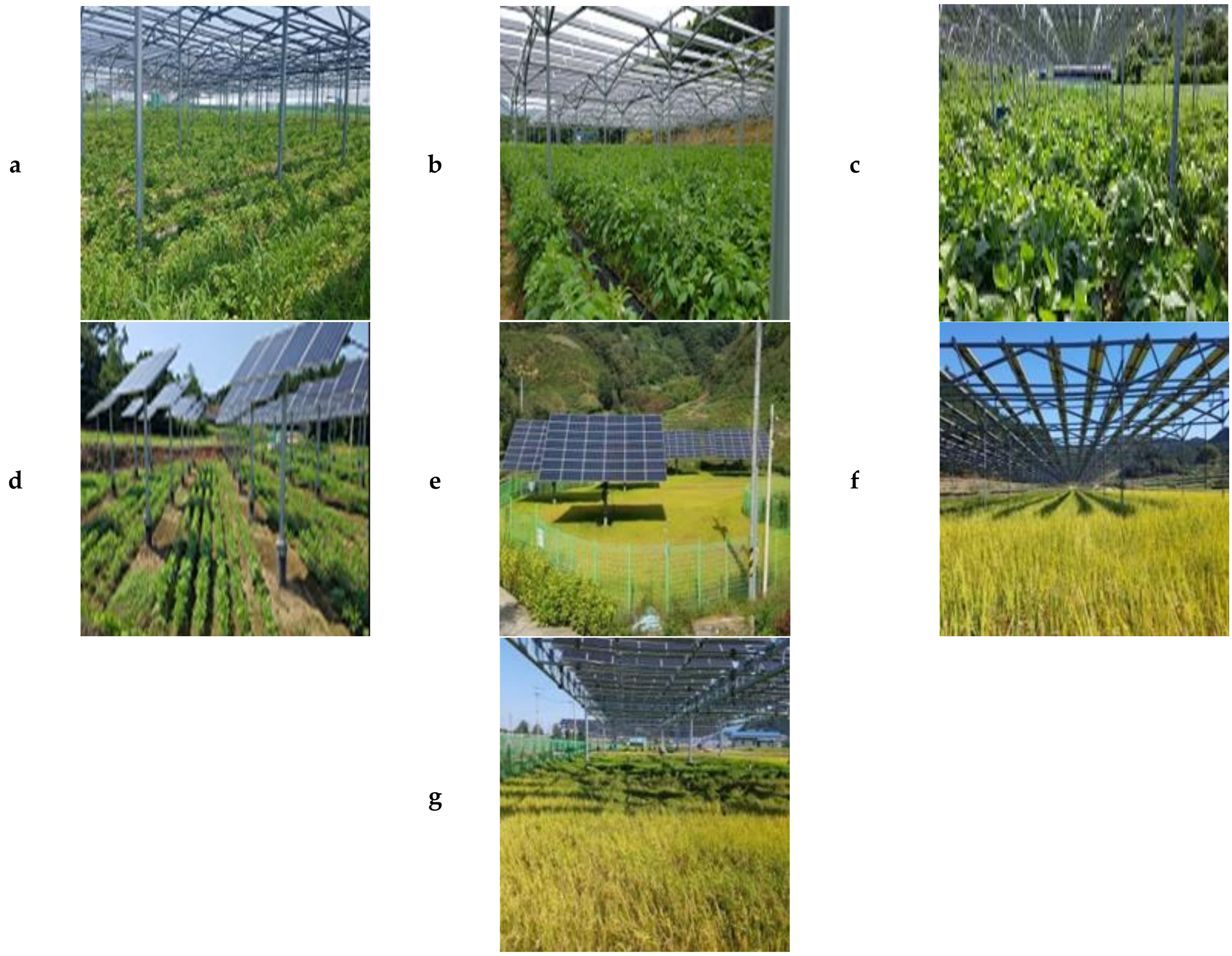

Figure 1. APV facilities used in this study (**a**), potato in Cheongju; (**b**), sesame in Gaesan; (**c**), soybean in Paju; (**d**), soybean in Youngkwang; (**e**), rice in Seungju, (**f**), rice in Boseong; (**g**), rice in Naju.

2.2. Growth and Cultivation Conditions under APV

For the potato study, potatoes (cv. Sumi) were planted in 20 × 100 cm spaces and covered with black vinyl mulch on 29 March 2021. The crop was harvested on 21 June 2021. Other cultivation conditions followed the standard Rural Development Administration cultivation methods.

At harvest, the plant height, stem number, stem diameter, leaf number, leaf length, and leaf width of the crops grown under the APV systems were measured. For comparison, these same parameters were measured in the crops grown in open, control plots neighboring the APV systems. When the yield components, such as tuber number and weight per plant, were measured, high (over 30 g of weight) and low-quality (less 30 g of weight) potatoes were also separated. In addition, the fresh shoot weight of the aboveground parts, tubers, and roots per plant was measured. The high-quality yield per 10a (1000 m^2) and total yield were also measured. Since potato crops did not significantly vary between the control crops and those grown underneath APV systems, we conducted another study in 2022 in order to confirm what was observed in 2021. For this study, potato was planted in 25 × 95 cm spaces on 24 March and harvested on 18 June 2022. Cultivation conditions were the same as those in our 2021 study.

For the sesame study, sesame (cv. Asankkae) was planted with colored vinyl mulching in 100 × 20 cm spaces on 28 April 2021 and harvested on 10 August 2021. The plant height, leaf number, and branching number of sesame were measured on 5 July 2021. At harvest, the stem length, stem diameter, branching number, effective branching number, ratio of effective branching, capsule length, capsule width, capsule number, seed number per capsule, 1000 seed weight, seed weight/m^2, and yield (1 m^2) were measured in both crops grown under the APV systems or in a control plot.

For the soybean study, soybean was planted by machine with the Jangdan cultivar in Paju and the Daewon cultivar in Youngkwang. The seeding date was 9 June 2021, and the planting distance was 80 × 10 cm in Paju. In Youngkwang, the seeding date was 3 July 2021, and the planting distance was 70 × 10 cm. The stem length, node number on the main stem, and stem diameter were measured on 10 July and 5 August in both Paju and Youngkwang. The pod weight, pod number per plant, seed number per plant, grain weight per plant, 100 seed weight, population number/m^2, liter weight, and yield (1 m^2) were measured at harvest in Paju and Youngkwang.

For the rice study, 15-day-old seedlings of rice (cv. Saecheongmu) were transplanted by machine in 30 × 15 cm spaces on 26 May 2021, in Seungju. Eighteen-day-old seedlings of rice (cv. Cheongmu) were transplanted by machine in 30 × 15 cm spaces on 31 May 2021, in Boseong. Fifteen-day-old seedlings of rice (cv. Ilmibyeo) were transplanted by machine in 30 × 16 cm spaces on 15 June 2021, in Naju. The fields were managed with N-P_2O_5-K_2O fertilization of 60-30-40 kg ha^{-1} for Seungju and 90-45-57 kg ha^{-1} for Boseong and Naju, respectively. The plant height and tiller number were measured on 9 July 2021, in Seungju and Boseong, and on 26 July 2021 in Naju. We measured 10 plants in each experimental plot for the plant height and tiller number. At harvest, the culm length, panicle length, panicle number per hill, spikelet number per panicle, ripening rate, 1000 seed weight, and yield were measured in Seungju, Boseong, and Naju. The crop yields were measured by harvesting from sample plants in each experimental plot (1 m^2). Standard chemical products were used to manage disease, insects, and weeds.

2.3. SPAD Value and Photosynthetic Efficiency

The SPAD value and photosynthetic efficiency were measured in crops grown under the APV facilities in Seungju. The SPAD value and photosynthetic efficiency of crops growing in the neighboring control plot were also measured for comparison. Twenty-five-day-old seedlings of paddy rice (cv. Saecheongmu) were transplanted by machine on 26 May 2022. The other cultivation conditions followed standard Rural Development Administration cultivation methods. The SPAD value of chlorophyll content was measured using a SPAD-502 Plus meter (KONICA MINOLTA Co., Ltd., Tokyo, Japan) at 10 (35 days after seeding) and 20 days (45 days after seeding) after transplanting. The electron transport rate (ETR) of photosynthetic efficiency was measured using a PAM-2500 (Heinz Walz GmbH, Effeltrich, Germany) 10 (35 days after seeding) and 20 days (45 days after seeding) after transplanting. The leaves were adapted in the dark for 20 min to measure their photosynthetic efficiency. We measured 10 plants from 1:00 p.m. to 2:00 p.m. in each experimental unit for SPAD values and ETR.

2.4. Meteorological Parameters

Meteorological instruments were installed to measure air temperature, soil temperature, and solar radiation in Seungju and Bosung, South Korea. The atmospheric temperature at the sites was obtained using temperature smart sensors (S-THC-M002, Onset Co., MA, USA), which were attached to metal poles 1.2 m above the ground. Site soil temperatures were measured using 12-Bit temperature smart sensors (S-TMB-M0002, Onset Co., MA, USA), which were placed at a soil depth of 3 cm. Photosynthetically active radiation (PAR, μmol m^{-2} s^{-1}), which is a unit of measurement that quantifies the light effect of solar energy at specific wavelengths, was also measured. The measurements were performed using a PAR smart sensor (S-LIA-M003, Onset Co., MA, USA). Solar radiation was measured using a Silicon Pyranometer smart sensor (S-LIB-M003, Onset Co., MA, USA). We installed sensors of meteorological instruments at two points in the field in each experimental unit. All data measured by the equipment were recorded at 10 min intervals.

2.5. Statistical Analysis

Data were collected from the area under the APV systems divided into three parts. The data were analyzed using the Statistical Analysis Systems software [25]. The means were separated using a *t*-test. p values < 0.05 were considered significant.

3. Results and Discussion

3.1. Growth and Yield of Various Crops Underneath APV Systems

The potato growth levels were evaluated by measuring the growth parameters, such as the plant height and leaf number (Table 2). The stem number per plant, stem diameter per plant, leaf number per plant, leaf length per plant, and leaf width per plant were similar in the crops grown under the APV system and in control plots. However, the plant height of the crops underneath the APV system was almost two times higher than in the control plot. Higher plant height underneath the APV system may be related to the shading rate caused by the APV panel.

Table 2. Growth of potato underneath an agrophotovoltaic (APV) system in Chongju, South Korea, 2021.

Condition	Plant Height (cm)	Stem Number /Plant	Stem Diameter (mm)/Plant	Leaf Number/Plant	Leaf Length (cm)/Plant	Leaf Width (cm)/Plant
APV	41.2 *	1.7	11.0	13.0	24.9	16.3
Control	24.9	2.1	10.8	11.6	24.9	17.4

* significantly different between APV system and control plot using a *t*-test (p = 0.05).

At harvest, tuber number and weight per hill were not significantly different between crops grown under APV systems and control plots (Table 3). The shoot fresh weights of the aboveground parts and roots per hill were similar. On the other hand, the shoot fresh weight of tuber underneath the APV system was significantly higher than in the control plots. In 2022, in order to reconfirm yield levels in crops grown underneath APV systems, we carried out an experiment at the same APV facility that was used in 2021 (Table 4). Consistent with the 2021 study, the growth and yield of potato crops did not vary significantly whether they were grown underneath APV systems or in control plots. However, in other studies, the potato tuber yield decreased by 38.2% in crops grown under

APV systems compared to the assumed conventional potato tuber yield [22]. In another study, the tuber number and tuber yield of potatoes was decreased by shading [17,18], but in regions with high solar irradiation, the yields were increased when shading was applied either during early plant development [17] or around 12 p.m. [18] Moreover, the shade pattern under the APV systems varies depending on the season and other factors. In this respect, the potato growth and yield in this study were not adversely affected when the crops were grown under APV systems.

Table 3. Yield of potato underneath an agrophotovoltaic (APV) system in Cheongju, South Korea, 2021.

Condition	Tuber Number per Hill		Tuber Weight per Hill (g)		Shoot FW. per Hill (g)	Tuber FW. per Hill (g)	Root FW. per Hill (g)	Yield of Good Quality (kg/ha)	Total Yield (kg/ha)
	Good Quality	Poor Quality	Good Quality	Poor Quality					
APV	4.6	1.1	427.0	10.4	124.7	437.4	7.3	21,130	21,650
Control	5.9	1.3	491.0	12.2	140.7	503.2	8.2	24,303	24,907

FW., fresh weight. A *t*-test result showed non-significant difference.

Table 4. Growth and yield of potato underneath an agrophotovoltaic (APV) system in Cheongju, South Korea, 2022.

	Plant Height	Stem Number	Leaf Number	Tuber Weight per Hill (g)		Yield of Good Quality (kg/ha)	Total Yield (kg/ha)
				Good Quality	Poor Quality		
APV	32.6	1.5	12.0	472.4	19.9	20,995	21,879
Control	24.9	2.3	12.2	529.4	14.2	23,313	24,089

A *t*-test result showed non-significant differences.

In the case of sesame crops, when the plant height, leaf number, and branching number were measured 58 days after seeding on 5 July 2021, all parameters underneath the APV were lower than the control plot (Figure 2). At harvest, the stem length, adequate branching number, 1000 seed weight, and yield underneath APV were also lower than the control plot (Table 5). On the other hand, the stem diameter, branching number, effective branching ration, capsule length, capsule width, capsule number, seed number per capsule, and seed weight/m^2 were not significantly different between the crops grown under the APV systems and in the control plots. Based on the authors' knowledge, this study is the first report on sesame crop production underneath the APV system.

Two APV facilities (Paju and Youngkwang) were used for the soybean study. The plant height and node number on the main stem underneath APV in Paju were significantly lower than the control plot 30 days after seeding (19 July 2021) (Figure 3). On the other hand, at 54 days after seeding (5 August 2021), the parameters were similar in the crops grown under APV systems and the control plots. The stem diameter underneath APV was significantly lower than the control plot at 54 days after seeding. In the Youngkwang APV system, the plant height and node number on the main stem were similar in crops grown under the APV systems and in control plots at 16 days after seeding (19 July 2021). In contrast, the node number on the main stem and stem diameter underneath the APV were lower than the control plot at 33 days after seeding (5 August 2021). Most parameters, such as pod weight, pod number per plant, seed number per plant, grain weight per plant, 100 seed weight, plant number/m^2, and liter weight at harvest, were similar in the crops grown under APV systems and in the control plots (Table 6). On the other hand, the ungrained ratio per pod underneath the APV was significantly higher than that in the control plot. Furthermore, the yield underneath the APV was reduced by 18% compared to the control plot. Similar to Paju, the ungrained ratio per pod underneath the APV in Youngkwang was significantly higher than the control plot. In addition, grain weight per plant underneath the APV was significantly lower than the control plot. The yield underneath was reduced by 20% compared to the control plot. Yield reduction underneath the APV in both Paju and Youngkwang may be caused by an increasing ungrained ratio per pod. In another study at a different APV facility, the soybean yield declined by 21% underneath the APV system compared to the control plot [26]. This APV system was a 20% solar radiation reduction regime.

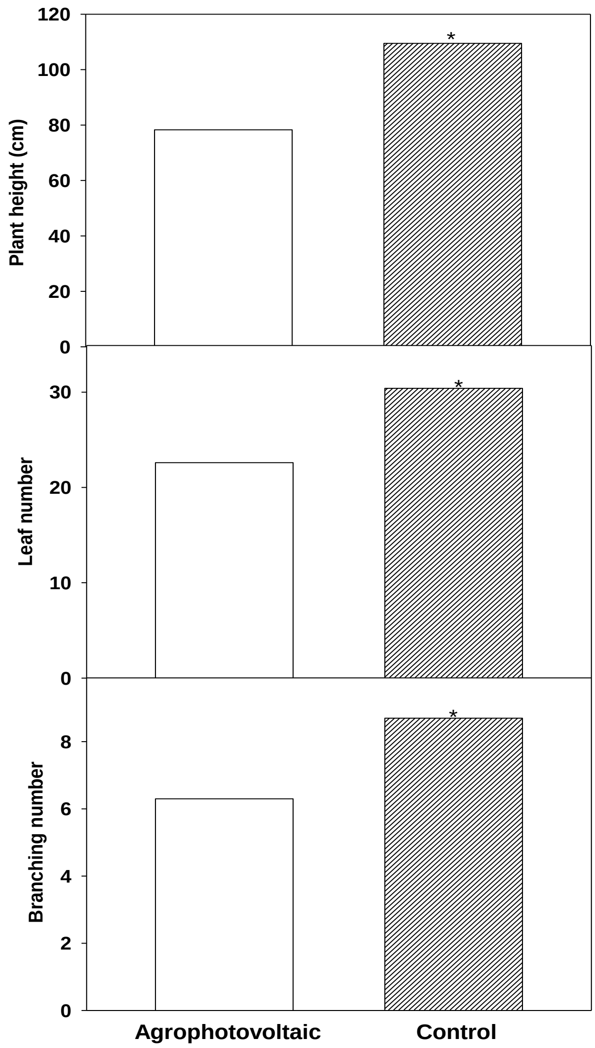

Figure 2. Growth of sesame underneath an agrophotovoltaic (APV) system in Goesan, South Korea. * significantly different between APV system and control plot using a *t*-test ($p = 0.05$).

Table 5. Growth and yield of sesame underneath an agrophotovoltaic (APV) system in Goesan, South Korea.

Condition	Effective Branching Number	Ratio of Effective Branching (%)	Capsule Length (mm)	Capsule Width (mm)	Capsule Number per Hill	Seed Number per Capsule	1000 Seed Weight (g)	Seed Weight (g/m^2)	Yield (kg/ ha)
APV	4.3	86.0	28.8	7.7	60.0	57.5	2.02	143	429
Control	5.1 *	86.4	29.4	7.6	68.2	60.9	2.24 *	176	528 *

* significantly different between APV system and control plot using a *t*-test ($p = 0.05$).

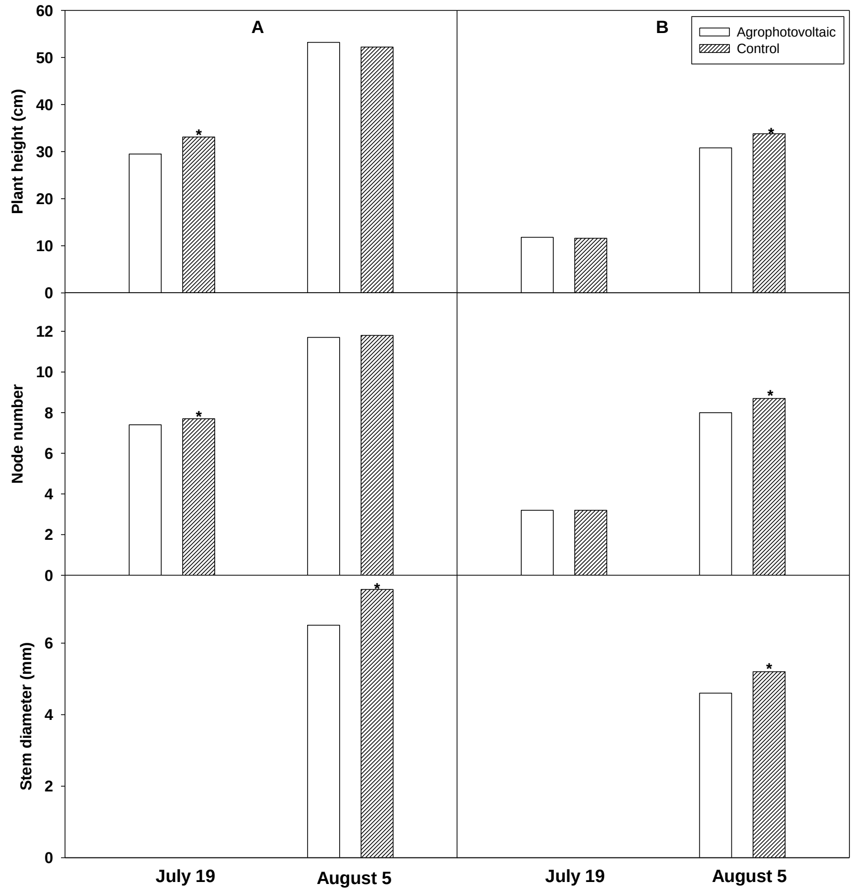

Figure 3. Growth of soybean underneath agrophotovoltaic (APV) systems in Paju (**A**) and Youngkwang (**B**), South Korea. * significantly different between APV system and control plot at different investigation dates using a *t*-test (p = 0.05).

Table 6. Growth and yield of soybean underneath agrophotovoltaic (APV) systems in Paju and Youngkwang, South Korea.

Area	Condition	Pod Weight (g)	Pod Number per Plant	Seed Number per Plant	Grain Weight per Plant (g)			Ungrained Ratio (%)	100 Seed Weight (g)	Plant Number (m^2)	Liter Weight (g/L)	Yield (kg/ha)
					Grain Weight	Ungrained Weight	Total					
Paju	APV	20.1	34.9	55.8	14.8	0.2	15.0	1.8 *	25.2	14.0	755.9	2029
	Control	24.8	40.9	64.7	16.9	0.3	17.2	0.8	25.9	16.0	732.1	2463 *
Young-kwang	APV	20.1	26.9	41.8	13.3	0.4	13.7	3.1 *	32.7	13.5	756.9	1665
	Control	27.2	33.5	53.4	18.7 *	0.4	19.1*	1.6	35.8	12.3	732.1	2092 *

* significantly different between APV system and control plot using a *t*-test (p = 0.05).

Three APV facilities were used (Seungju, Boseong, and Naju) for the rice study. The plant height at 44 days after transplanting in Seungju and 39 days after transplanting in Boseong was similar in the crops grown under the APV systems and control plots (Figure 4). On the other hand, the plant height 41 days after transplanting underneath the APV in Naju was higher than that of the control plot. The tiller number in Seungju and Boseong was similar in the crops grown under the APV systems and control plots. In contrast, the tiller number underneath the APV in Naju was lower than that of the control plot. At harvest, the culm length, panicle length, spikelet number per panicle, and ripening rate in Seungju were similar in the crops grown under APV systems and control plots (Table 7). The panicle number per hill and 1000 seed weight underneath APV were lower than the control plot. The yield underneath the APV was reduced by 13% compared to the control plot. The yield may be reduced because of the panicle number per hill and 1000 seed weight. In the case of Boseong, the panicle length and panicle number per hill were not significantly different between the crops grown under the APV systems and in the control plots. On the other hand, the spikelet number per panicle, ripened grain, 1000 seed weight, and yield were significantly lower underneath the APV system than in the control plot. In contrast, the culm length underneath the APV system was significantly higher than that of the control plot. The yield underneath APV was reduced by 14% compared to the control plot. The lower yields could be caused by spikelet number per panicle, ripened grain, and 1000 seed weight. In the Naju APV system, the panicle length, panicle number per hill, and ripened grain were not significantly different between the crops grown under the APV systems and in control plots. On the other hand, spikelet number per panicle, 1000 seed weight, and yield underneath the APV system were significantly lower than those of the control plot. Similar to rice crops grown in Boseong under APV systems, the culm length underneath the APV systems was significantly higher than that of the control plot. The yield underneath the APV was reduced by 30% compared to the control plot. This decrease in yield was attributed to the spikelet number per panicle and 1000 seed weight. Overall, the yield was reduced by 13–30% in three APV systems. The yield reduction may be related to many factors, such as the shading rate of APV, cultivars, and cultivation methods. The extent of yield reduction depends on the shading level, time period, and the stage of crop development under which the shading was applied. For example, rice yield can be reduced by up to 73% under severe shading conditions, with aa reduction of incoming radiation of up to 77% [27]. In the APV system, however, the shading conditions are constant during all crop growth and development stages. In Japan, a 20% reduction in solar radiation underneath an APV led to a 20% reduction in rice yield [23]. In South Korea, the rice yield underneath three different APV facilities (Gosung, Jeongju, and Naju) was approximately 20% lower than the control plot [26,28,29]. From these results, it was assumed that the reduction of rice yield underneath the different APVs was similar regardless of the APV facilities with different shading rates and types of fixing and tracing for light.

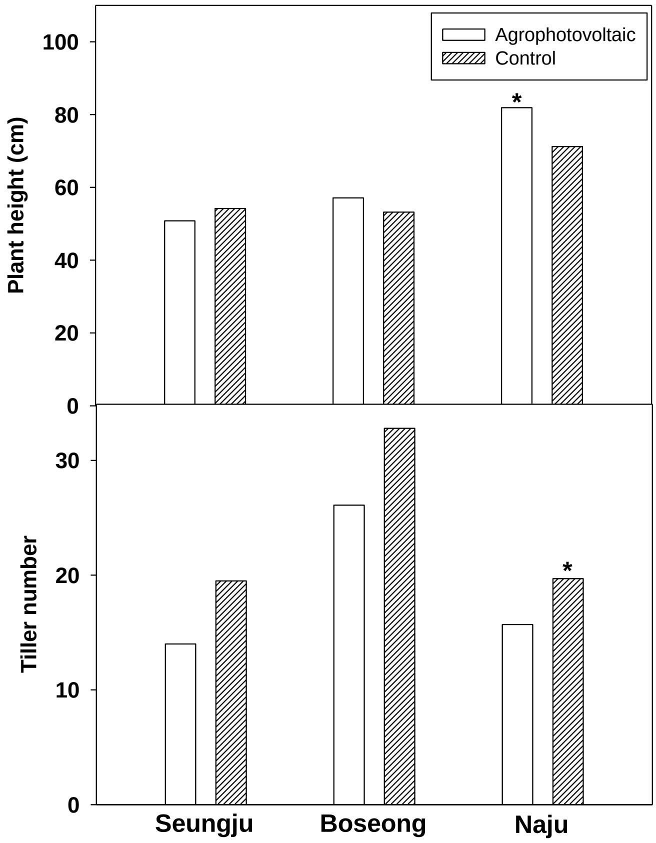

Figure 4. Growth of rice underneath agrophotovoltaic (APV) systems in different areas of South Korea. * significantly different between each APV system and control plot using a *t*-test ($p = 0.05$).

Table 7. Yield of rice underneath agrophotovoltaic (APV) systems in different areas of South Korea.

Area	Condition	Culm Length (cm)	Panicle Length (cm)	Panicle Number per Hill	Spikelet Number per Panicle	Ripen Grain (%)	1000 Seed Weight (g)	Yield (kg/ha)
Seungju	APV	69.8	17.2	11.8	75.0	81.0	26.7	5248
	Control	68.6	16.6	13.8 *	77.8	86.2	27.4 *	6037 *
Boseong	APV	88.2 *	17.8	17.2	70.0	77.3	26.4	5537
	Control	78.8	18.4	18.1	75.4 *	87.1 *	27.8 *	6464 *
Naju	APV	81.2 *	19.2	14.0	94.3	86.1	27.0	6040
	Control	75.3	19.5	15.8	104.8 *	91.6	27.8 *	8580 *

* significantly different between APV system and control plot using a *t*-test ($p = 0.05$).

3.2. SPAD Value and Photosynthetic Efficiency

The parameters 10 and 20 days after transplanting were measured to determine the SPAD value (chlorophyll content) and photosynthetic efficiency between rice plants grown under APV systems and in control plots. The SPAD values underneath the APV system 10 days after transplanting were lower than in the control plots (Figure 5). On the other hand, the SPAD values 20 days after transplanting were similar in the rice plants grown under the APV systems and control plots. Similar to the SPAD values, the electron transport rate (ETR) underneath the APV system 10 days after transplanting was lower than in the control plots (Figure 6). Although the ETR underneath the APV system 20 days after transplanting was lower than in the control plot, the ETR was not critically different under both conditions. In another study, the ETR underneath APV in rice and soybean was lower than in the control plot [20].

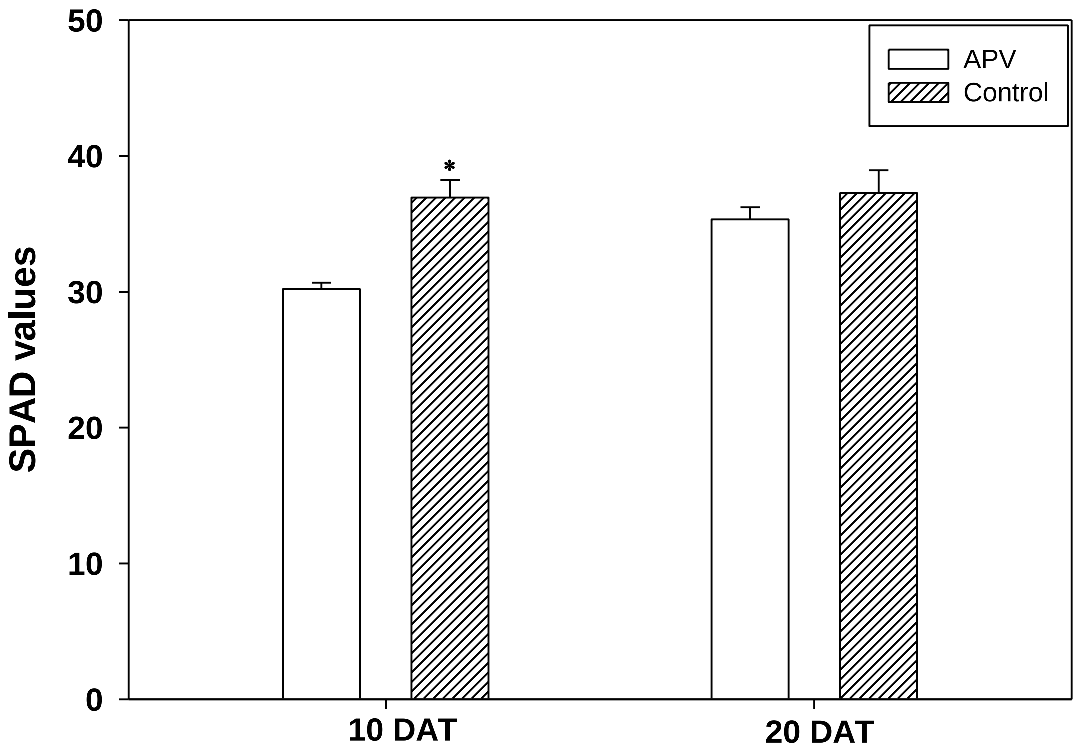

Figure 5. SPAD values of rice plants at 10 and 20 days after transplanting (DAT) underneath an agrophotovoltaic (APV) system, Seungju, South Korea. Error bars represent standard deviation. * significantly different between APV system and control plot at different investigation dates using a *t*-test ($p = 0.05$).

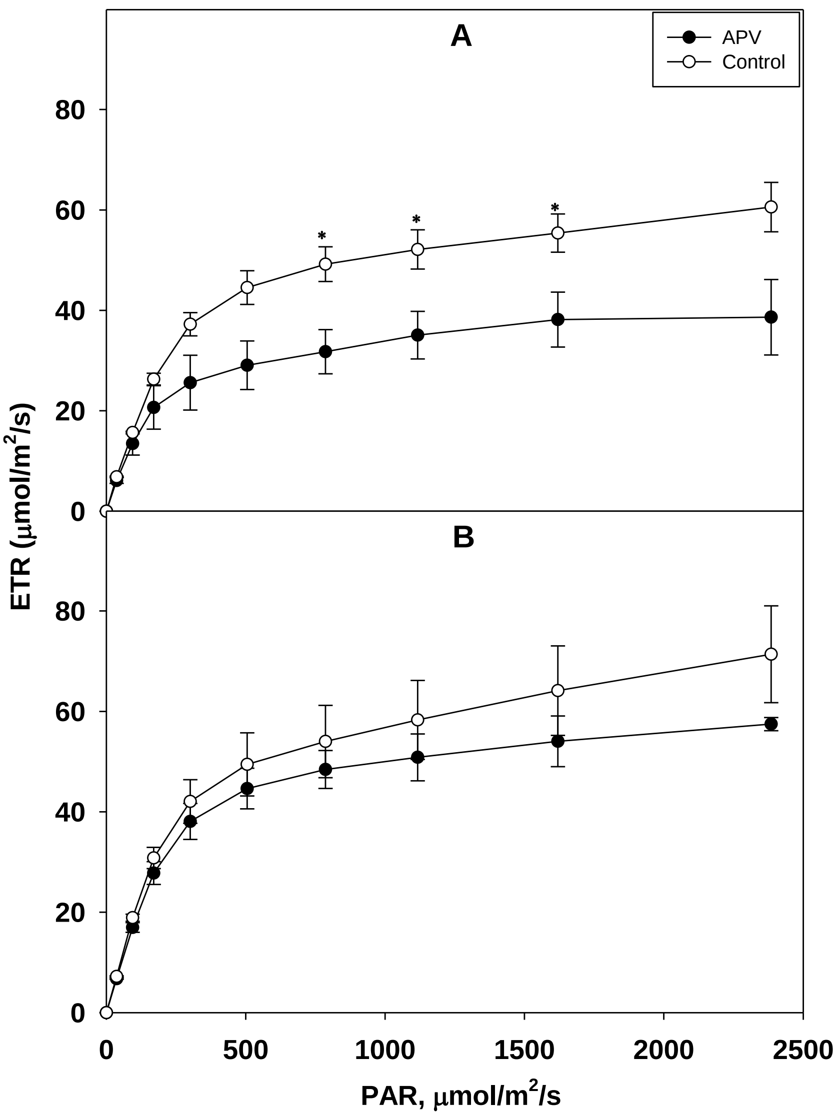

Figure 6. Effect of various PARs on ETR of rice plants at 10 (**A**) and 20 days (**B**) after transplanting (DAT) underneath an agrophotovoltaic (APV) system, Seungju, South Korea. Error bars represent standard deviation ($n = 3$). * significantly different between APV system and control plot using a t-test ($p = 0.05$).

3.3. Differences in Meteorological Parameters between APV Facilities and Control Plots

The solar radiation, photosynthetically active radiation (PAR), air temperature, and soil temperature during rice cultivation in Seungju and Boseong were measured to understand the cause of the yield reduction in crops grown underneath the APV systems. During September in Seungju, the solar radiation and PAR were lower in the APV systems than in the control plot (Figure 7). During August in Boseong, where a different APV system was used, the solar radiation and PAR were also lower than the control plot. Furthermore, solar radiation from 6:00 a.m. to 6:00 p.m. (3 September 2021) in Seungju was lower than that of the control plot (Figure 8). During this time, the greatest reduction in solar radiation underneath the APV system was at 11:00 a.m. At this time, the solar radiation was reduced by 57% compared to the control plot. Furthermore, the PAR from 6:00 a.m. to 6:00 p.m. (3 September 2021) in the Seungju APV system was lower than that of the control plot. The air temperature from 6:00 a.m. to 6:00 p.m. (3 September 2021) was generally similar under the Seungju APV system and the control plot. On the other hand, the air temperature in the control plot from 10:00 a.m. to 1:00 p.m. (3 September 2021) was slightly higher than under the APV system. The soil temperature from 10:00 a.m. to 1:00 p.m. (3 September 2021) was similar at both locations in Seungju.

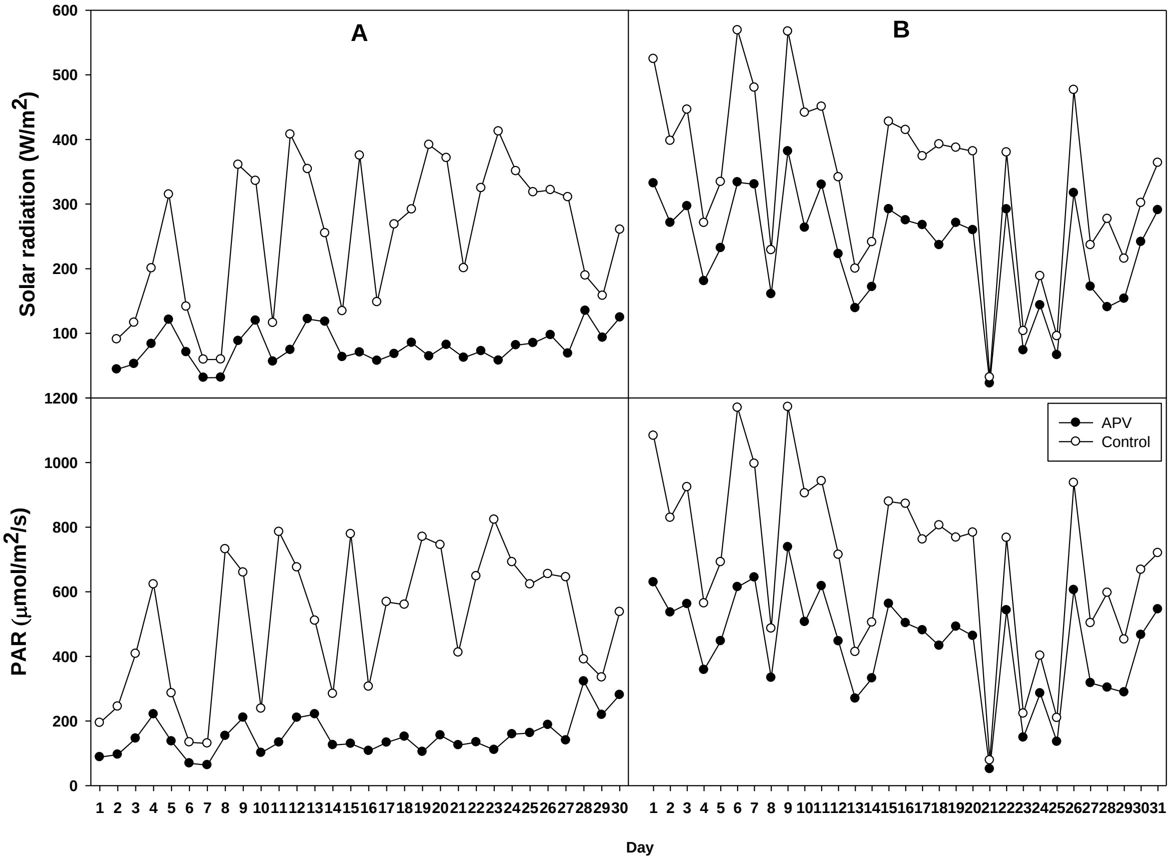

Figure 7. Solar radiation and PAR underneath APV stems in Seungju ((**A**), September) and Boseong ((**B**), August), South Korea.

In Boseong, the solar radiation from 6:00 a.m. to 6:00 p.m. (3 September 2021) was lower under the APV systems than in the control plot; the PAR was also reduced similarly (Figure 9). The greatest reduction in solar radiation under the APV system was at 1:00 p.m. (38% reduction compared to the control). The air temperature from 6:00 a.m. to 6:00 p.m. (3 September 2021) underneath the APV system in Boseong was similar to the control plot. The soil temperature was similar at both locations in the morning, but at 1:00 p.m., the control plot soil temperature was less than 1 °C higher than the soil temperatures under the APV system.

The reduction in solar radiation underneath the APV canopy is expected to be the most apparent change, and several other microclimate factors may also be altered. In the present study, however, the air and soil temperatures were similar under the APV systems and the control plots. Marrou et al. [21] did not find any significant changes in the daily mean temperatures between an APV system and a control plot at the French location of Montpellier. On the other hand, other studies found that the soil and maximum air temperatures were lower in the shaded areas compared to full-sun conditions [30,31]. Crop cultivation often suffers from the adverse effects of high solar radiation. In other studies of rice cultivation, solar radiation under the APV systems was approximately 30–42% less than in their respective control plots [32,33]. These results were similar to those of the APV systems in Boseong and Seungju used in this study. The extent of the reduction in solar radiation under the APV systems depend on the APV facility, measuring times, seasonal solar altitude, the position underneath the array, and the technical implementation of the facility.

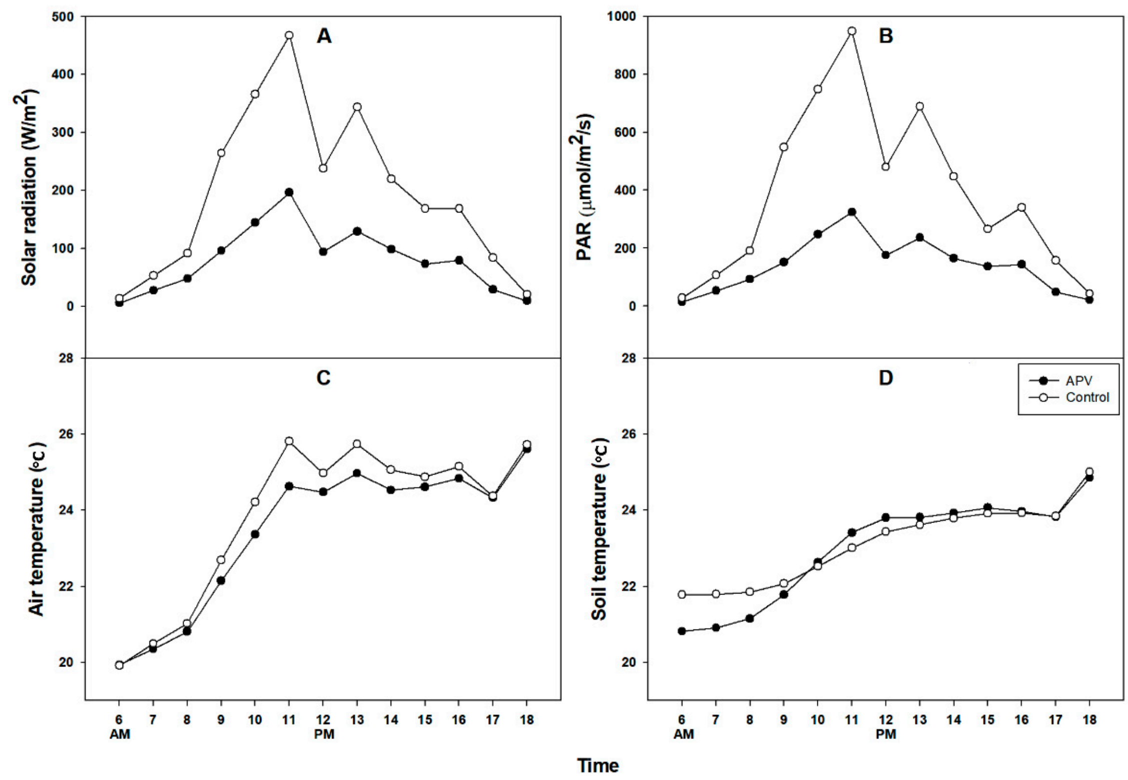

Figure 8. Solar radiation (**A**), PAR (**B**), air temperature (**C**), and soil temperature (**D**) from 6:00 to 18:00 (3 September) underneath APV system in Seungju, South Korea.

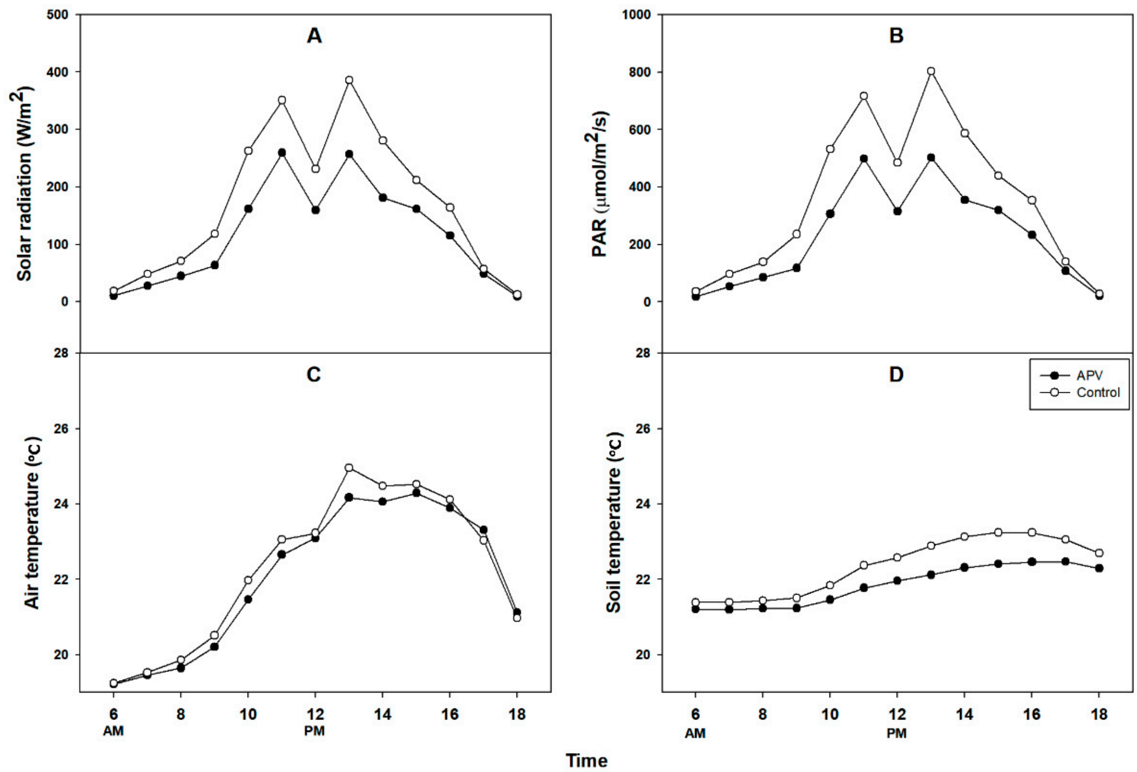

Figure 9. Solar radiation (**A**), PAR (**B**), air temperature (**C**), and soil temperature (**D**) from 6:00 a.m. to 6:00 p.m. (3 September) underneath APV system in Boseong, South Korea.

4. Conclusions

The potato yield was similar in the APV system and the control plot. On the other hand, the yields of sesame, soybean, and rice crops grown underneath the APV systems were 19%, 18–20%, and 13–30% lower than those grown in the control plot, respectively. The SPAD and photosynthetic efficacy in the rice plants grown underneath the APV systems were also lower than in the control plots.

The reduction of light resources could be directly responsible for the slower growth and development of crop plants in the shade. Based on the experimental results, the upper limits of the shading rate ranged from 25–32%. Furthermore, solar radiation and PAR underneath the APV systems were lower than in the control plots. These factors may adversely affect the crop yield. The crop yield is also influenced by multiple conditions (i.e., temperature, CO_2 concentration, soil nutrients, and water) and cultivation methods. Thus, using APV systems requires modifications in terms of the shading effects of the system and using the appropriate crops for the fluctuating shade [15,21]. In addition to shading, the light requirements of each crop used in the APV should be chosen and managed carefully [14]. Thus, the effects of shading must be considered when exploring potential APV conditions. This result implies that the APV system could be applicable to potato without yield reduction.

Author Contributions: Data curation, H.J.L., H.H.P., and Y.O.K., writing, review, and editing, Y.I.K. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Korea Institute of Planning and Evaluation for Technology in Food, Agriculture and Forestry (IPET) through the Agricultural Energy Self-Sufficient Industrial Model Development Program, funded by the Ministry of Agriculture, and Food and Rural Affairs (MAFRA) (Project No. 321075022HD020).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare that they have no conflict of interest.

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