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Solar Sharing for Both Food and Clean Energy Production: Performance of Agrivoltaic Systems for Corn, A Typical Shade-Intolerant Crop

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Abstract: The purpose of this research was to examine the performance of agrivoltaic systems, which produce crops and electricity simultaneously, by installing stilt-mounted photovoltaic (PV) panels on farmland. As PV power stations enjoy remarkable growth, land occupation with the purpose of establishing solar farms will intensify the competition for land resources between food and clean energy production. The results of this research showed, however, that the stilt-mounted agrivoltaic system can mitigate the trade-off between crop production and clean energy generation even when applied to corn, a typical shade-intolerant crop. The research was conducted at a 100-m^2 experimental farm with three sub-configurations: no modules (control), low module density, and high module density. In each configuration, 9 stalks/m^2 were planted 0.5 m apart. The biomass of corn stover grown in the low-density configuration was larger than that of the control configuration by 4.9%. Also, the corn yield per square meter of the low-density configuration was larger than that of the control by 5.6%. The results of this research should encourage more conventional farmers, clean energy producers, and policy makers to consider adopting stilt-mounted PV systems, particularly in areas where land resources are relatively scarce.

Keywords: agrivoltaic systems; stilt-mounted photovoltaic panels; shade-intolerant crops

1. Introduction

Our society relies heavily on fossil fuels, which is not sustainable. In contrast to fossil fuels, renewable energy resources are constantly replenished and more environmentally friendly. Commonly used renewable energy sources include biomass, hydropower, geothermal, wind, and solar. Among renewable energy technologies, photovoltaic (hereafter called "PV") power generation has enjoyed remarkable growth over the past decade. According to the International Energy Agency (hereinafter called "IEA"), the installed capacity of PV in major countries was approximately 402 GW in 2017, 70 times higher than in 2006.

As PV power stations continue to enjoy remarkable growth, land occupation intended for solar farms will intensify competition for land resources between food and clean energy production [1]. The question remains as to how competition for land resources between food and energy production can be resolved. Although PV systems require less land than other renewable energy options [2], in reality, commercial PV power stations can occupy a considerable land area at local scales. In many cases, the most suitable sites for solar power plants, which perform optimally with long daylight hours and minimal cloud cover, are classified as agricultural land. This presents an issue, in that land supporting viable and diverse agriculture is likely to have more value as agricultural land than as a solar farm [3]. This competiti'on could be particularly serious in densely populated regions, mountainous areas, and small inhabited islands.

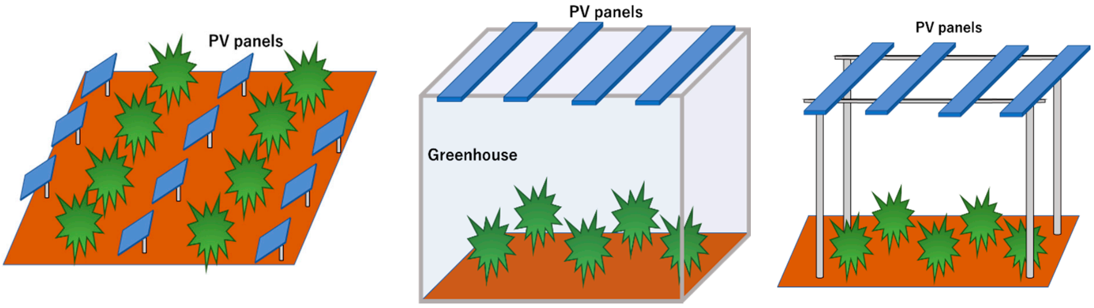
However, this competition could be reduced by agrivoltaic systems, which produce crops and electricity at the same time by installing compact solar panels on farmland. Although previous studies have indicated that this system effectively produces shade-tolerant crops and electricity simultaneously [4], further studies are required to evaluate its practical applications. In particular, the performance of shade-intolerant crops, which are expected to grow poorly in low-light environments, has not yet been fully explored for agrivoltaic systems.

1.1. Research Significance and Objectives

The fundamental problem tackled by this research was how to reduce competition for land resources between food production and PV power generation. In other words, the main objective was to identify a PV system that can help reduce the tension between limited land resources and increasing demands for food and clean energy. Roof-top PV systems can partially satisfy home electricity demands, but other sectors consume more electricity. As a major renewable energy source, large (commercial-scale) PV power stations are key to meeting the demands of those sectors. Although commercial PV power stations nevertheless occupy vast tracts of land at local scales, this problem could be solved by agrivoltaic systems.

1.2. Background

To date, three types of agrivoltaic systems, which simultaneously enable crop and electricity production on farmland, have been proposed (Figure 1). The first type was proposed in the early 1980s, using the space between PV rows for crops [5]. The second type is a PV greenhouse, in which part of its transparent covering is replaced by PV modules. The use of PV for greenhouses is a promising solution for the competition for land resources between food and energy production because it allows continuous food production and electricity generation throughout the year [6]. The third type consists of stilt-mounted PV modules above the crops.



(**a**) (**b**) (**c**)

Figure 1. Three different types of agrivoltaic system: (**a**) using the space between photovoltaic (PV) panels for crops, (**b**) a PV greenhouse, and (**c**) a stilt-mounted system.

Stilt-mounted agrivoltaic systems were originally invented in 2004 [7]. The structure is made of pipes and rows of PV panels mounted above the ground and arranged at certain intervals to allow enough sunlight for photosynthesis to penetrate to the ground. The system is designed to guarantee adequate sunlight for crops and sufficient space for agricultural machinery. Moreover, the structure has no concrete footing, so it can be easily dismantled.

Existing studies have focused on agrivoltaics with stilted solar arrays. Farm experiments with stilt-mounted PV modules were recently reported in France [4], Japan [8], and the United States [9]. They indicated that the system of planting shade-tolerant crops does not decrease land productivity. Adoption of agrivoltaic systems may therefore require minimal adaptation of cropping practices. The first reported agrivoltaic farm experiment was performed in Montpellier, France in 2013 [4]. They grew lettuce crops with a system consisting of 0.8-m-wide stilt-mounted PV modules, mounted at a height of 4 m and tilted at an angle of 25°. The same area of land was used to successfully produce both electricity and food. Their results showed that shading created by the PV arrays had no significant effect on the lettuce yield. The growth rate below the PV panels was not reduced except during the juvenile phase of the crop.

Interestingly, field experiments performed by Dupraz and colleagues found that agrivoltaic systems even increased land productivity for durum wheat by 35–72% [10]. They used land equivalent ratios to compare conventional options (separation of agriculture and energy harvesting) and two agrivoltaic systems with different PV panel densities. Light transmission at the crop level by an array of solar panels was modeled, and a crop model was developed to predict the productivity of partially shaded crops. According to another field experiment, solar-generated electricity coupled with shade-tolerant lettuce production resulted in an increase in economic value of over 30% over conventional agriculture [11].

1.3. Gaps in Current Agrivoltaics Research

In order to evaluate the practical value of agrivoltaic systems, however, further studies are required. For example, the potential of PV greenhouses has yet to be explored as previous farm experiments have mainly focused on agrivoltaic systems consisting of stilt-mounted PV modules above crops. Nevertheless, further research on stilt-mounted PV systems is still vital, particularly in terms of their application to shade-intolerant crops.

The studies reviewed above only indicate that agrivoltaics are effective for plants that are shade tolerant: namely arugula, Asian greens, chard, collard greens, kale, mustard greens, parsley, sorrel, spinach, scallions, broccoli, kohlrabi, cabbage, hog peanut, alfalfa, yam, taro, cassava, and sweet potato [11]. However, the effectiveness of the system for shade-intolerant crops, which are expected to grow poorly in a low-light environment, has not yet been explored. Many major commercial crops, such as corn, watermelon, tomato, cucumber, pumpkin, cabbage, turnip, and rice, are shade-intolerant and presumably require abundant sunlight. If agrivoltaics are only applicable to commercially less viable and shade-tolerant crops, the system is not likely to produce enough food and clean energy to meet the increasing global demand.

However, it is meaningful to study the possibility of coupling agrivoltaic systems with shade-intolerant crops. It is important to check whether an increase in the overall productivity of land could be achieved even with crops that need plenty of sunlight. Shade-tolerance is a plant trait that describes its ability to tolerate low light levels. Only limited screening studies of crop tolerance to shade are available [12,13]. In practice, corn, watermelons, tomatoes, and taro are reputed to have high saturation points, which means that they need strong light to grow. Examples of crops that prefer moderate light include cucumbers, turnips, pumpkins, cabbage, and green peppers. Mushrooms show a preference for growth in comparatively dark places.

1.4. Research Questions, Hypotheses, and Specific Aims

The goal of this research was to examine the effectiveness of agrivoltaic systems at reducing the tensions between limited land resources and increasing demands for food and clean energy. Particularly, this research focused on the stilt-mounted type of agrivoltaic system, which is the most widely adopted system in existing studies and practice. In order to achieve this goal, the research considered the following related questions: 1) Is it possible to grow shade-intolerant crops under the shade of agrivoltaic PV panels? 2) Can stilt-mounted agrivoltaic systems mitigate the trade-off between crop production and clean energy generation even when applied to shade-intolerant crops?

Therefore, the hypotheses examined in this research were as follows:

- The biomass of corn stover grown in an agrivoltaic farm will be no less than 90% that of corn plants grown without the agrivoltaic system (stover refers to the dried stalks and leaves of a field crop).

- The annual revenue from PV power generation and corn harvest in an agrivoltaic farm will be larger than that of a traditional corn field.

2. Materials and Methods

Data necessary for this research were collected from a case study plot at the agrivoltaic experimental farm operated by the CHO Institute of Technology in Ichihara City, Chiba Prefecture, Japan (Latitude: 35.378929, Longitude: 140.138549).

2.1. Data Collection

The size of the experimental farm was 100 m^2 and contained three sub-configurations: no modules (control), low module density, and high module density (Figure 2). The solar PV modules were mounted on the ground, with the area underneath the stilts used for agriculture and large enough to accommodate farming equipment. The total output capacity of the PV system was 4.5 kW. The feed-in-tariff rate of 48 yen (approximately 0.44 USD) per kWh was secured for this PV system.

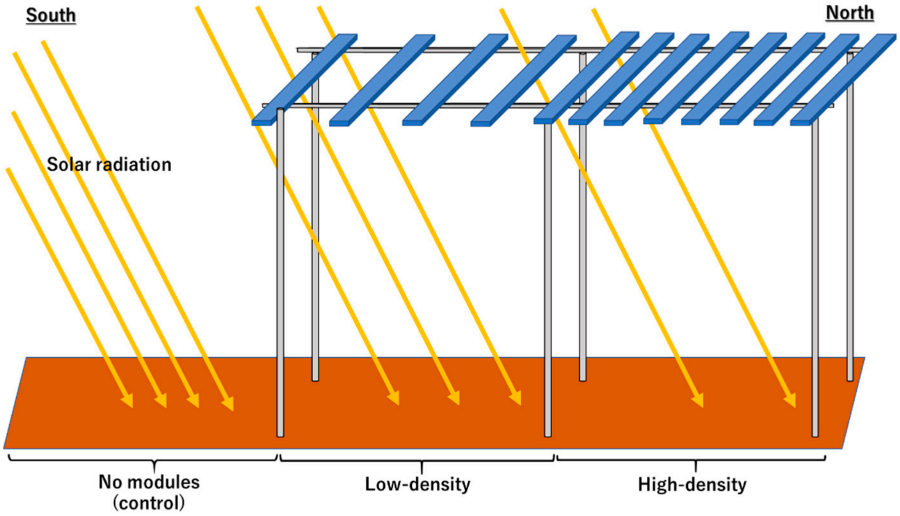


Figure 2. PV module configurations at the agrivoltaic experimental farm.

This system consisted of 72 PV modules (1354 mm × 345 mm) mounted at a height of 2.7 m and tilted at an angle of 30°. In the high-density configuration, there were eight PV module arrays (48 modules) spaced at 0.71 m intervals. In the low-density configuration, there were four PV module arrays (24 modules) spaced at 1.67 m intervals. Both the stilt-mounted PV panel configurations cast shade on the crop below. Although there was shade on the crop during some parts of the day, the crop was in full sunshine during some other parts of the day due to the sun's transit across the sky. Also, the shading from the PV module varied according to the time of year and height of the crops. The no-module (control) configuration had no PV modules above the ground.

The PV modules used in this research had a self-cleaning glass surface. Farming equipment spreads dust, which causes the soiling of the PV modules and affects the electricity output. This dust diminishes the transmittance capacity of the transparent collectors on the PV module surface. Therefore, periodic cleaning of the panels is required to maintain optimum power output. The PV modules in this research, however, could maintain clean surfaces without the need for frequent cleaning.

For this research, sweetcorn was planted on the experimental farm in early April 2018 and harvested in late July. Corn is a typical shade-intolerant crop and a major global commodity. Corn has a growth period of approximately 90 days and grows up to a height of 2 m. In each configuration, there were nine stalks per 1 m^2 spaced 0.5 m apart. The same soil, fertilizer, and water were used to grow all corn crops. The experimental farm adopted organic farming. Before planting, magnesia lime and oil cake (2 L per m^2) were scattered for neutralization. After planting, cow dung (2 L per m^2)

was scattered once. No pesticides were used. After harvesting, the weight, size, and market value of the reproductive part of the crop were evaluated. The market value was calculated using the 5-year average of the market price obtained by the Agriculture & Livestock Industries Corporation, a Japanese governmental agency.

2.2. Sensitivity Analysis

This research evaluated the sensitivity of the corn yield per square meter with respect to changes in the level of shading. If the biomass of corn plants grown in an agrivoltaic farm is no less than 90% of that of corn plants grown separately, the corn can be said to grow well under the shade of agrivoltaic PV panels. Thus, this research tested this hypothesis using Equation (1). Here, $B_{\mathrm{C(trad)}}$ is the traditional amount of crop biomass (dry basis) per square meter without an agrivoltaic installation, and B_{C} is the amount of the crop biomass per square meter with agrivoltaic intervention:

$$90\% \times B_{\mathrm{C(trad)}} \leq B_{\mathrm{C}} \tag{1}$$

Also, when the annual revenue from PV power generation and corn harvest in an agrivoltaic farm is larger than that of a traditional corn field, Equation (2) should be true, where $V_{\mathrm{C(trad)}}$ is the traditional value of the crop per square meter per year without an agrivoltaic installation, V_{C} is the revenue of the crop per square meter per year with agrivoltaic intervention, and S is the solar revenue per square meter per year:

$$V_{\mathrm{C(trad)}} < (V_{\mathrm{C}} + S) \tag{2}$$

3. Results

To examine the corn production performance of the experimental agrivoltaic farm, this research explored the sensitivity of corn yield per square meter to changes in shading level.

3.1. Corn Yield

The growth of corn planted under the PV modules was gauged in terms of the fresh weight of corn crops as well as the biomass of corn stover. As mentioned earlier, the corn was planted in early April 2018 and harvested in late July. Surprisingly, the corn yield of the low-density configuration was larger not only than that of the high-density configuration, but also than that of the no-module control configuration (Tables 1 and 2). The relationship between the crop biomass per square meter in the low-density configuration ($B_{\mathrm{c(low)}}$) and the crop biomass per square meter without the agrivoltaic PV modules ($B_{\mathrm{C(trad)}}$) is shown by the following equations:

$$\begin{gathered} B_{\mathrm{C(low)}}/B_{\mathrm{C(trad)}} = 1.049 \\ \therefore B_{\mathrm{C(trad)}} < B_{\mathrm{C(low)}} \end{gathered} \tag{3}$$

Similarly, the relationship between $B_{\mathrm{c(high)}}$, the crop biomass per square meter in the high-density configuration, and $B_{\mathrm{C(trad)}}$ is shown in the following equations:

$$\begin{gathered} B_{\mathrm{C(high)}}/B_{\mathrm{C(trad)}} = 0.969 \\ \therefore 90\% \times B_{\mathrm{C(trad)}} < B_{\mathrm{C(high)}} \end{gathered} \tag{4}$$

Table 1. Average fresh weight of corn crops grown in different configurations.

	Configurations		
	Control	**Low-Density**	**High-Density**
Average fresh weight (g)	372.2	393.0	358.8
Comparison with control	1	1.056	0.964

Table 2. Average biomass (dry basis) of corn stover grown in different configurations.

	Configurations		
	Control	**Low-Density**	**High-Density**
Average biomass (kg/m^2)	1.63	1.71	1.58
Comparison with control	1	1.049	0.969

The corn yield depends on the shading. Shading affects the amount of incident solar irradiation, which in turn affects the yield including the weight of crops and biomass of plants. The sensitivity of the corn yield can be described as the change in the fresh weight of reproductive parts and the amount of biomass (dry basis) of corn stover with respect to the spacing between modules.

The crop yield (Y) can be calculated by

$$Y\ [\mathrm{kg/m^2}] = (W \times d)/1000 \tag{5}$$

where W is the average fresh weight of crops (g) and d is the number of plants per square meter, which is nine in this study. Values of W for the control configuration, low-density configuration, and high-density configuration are 372.2, 393.0, and 358.8, respectively, which resulted in the low-density configuration exhibiting the highest corn yield, as shown in Table 3.

Table 3. Corn yields per square meter for different configurations.

	Configurations		
	Control	**Low-Density**	**High-Density**
Corn yield (kg/m^2)	3.35	3.54	3.23

3.2. *Performance of the PV System*

The monthly kWh output of the PV modules for different configurations is shown in Tables 4 and 5. The high-density configuration produced double the electricity per square meter than the low-density configuration. In other words, although the low-density configuration was able to exploit more sunlight for the crop plants underneath the PV modules, it clearly has a reduced PV output compared with the high-density configuration.

Table 4. Power output (kWh) of stilt-mounted agrivoltaic PV modules in the high-density configuration from September 2017 to August 2018.

Year	Month	kWh per Day	kWh per Month	kW per m^2	Revenue per m^2 (Yen)	Revenue (Yen)
2017	9	2.55	227	9.09	436	10,912
2017	10	1.65	142	5.68	273	6816
2017	11	1.74	171	6.85	329	8224
2017	12	1.80	150	6.00	288	7200
2018	1	1.99	183	7.33	352	8800
2018	2	2.36	218	8.72	419	10,464
2018	3	2.99	267	10.69	513	12,832
2018	4	3.64	303	12.13	582	14,560
2018	5	3.79	373	14.91	716	17,888
2018	6	2.73	236	9.44	453	11,328
2018	7	3.97	355	14.19	681	17,024
2018	8	3.65	348	13.92	668	16,704
Total			2974	118.96	5710	142,752

Table 5. Power output (kWh) of stilt-mounted agrivoltaic PV modules in the low-density configuration from September 2017 to August 2018.

Year	Month	kWh Per Day	kWh Per Month	kWh Per m^2	Revenue Per m^2 (Yen)	Revenue (Yen)
2017	9	2.546	114	4.55	218	5456
2017	10	1.645	71	2.84	136	3408
2017	11	1.745	86	3.43	164	4112
2017	12	1.800	75	3.00	144	3600
2018	1	1.987	92	3.67	176	4400
2018	2	2.363	109	4.36	209	5232
2018	3	2.994	134	5.35	257	6416
2018	4	3.640	152	6.07	291	7280
2018	5	3.795	186	7.45	358	8944
2018	6	2.735	118	4.72	227	5664
2018	7	3.973	177	7.09	340	8512
2018	8	3.654	174	6.96	334	8352
Total			1487	59.48	2855	7,1376

3.3. Crop Revenues

The revenue per square meter from crop yields can be calculated by

$$V_c\ [\text{yen/m}^2] = Y \times P \tag{6}$$

where Y is the average fresh weight of crops (kg) and P is the wholesale price of the crop per kg. According to data from the Agriculture & Livestock Industries Corporation, the historical prices of sweetcorn produced in Chiba prefecture over a period of 5 years from 2013 through 2017 are shown in Table 6. Using the 5-year average price, the revenue of corn grown in the different configurations was calculated (Table 7).

Table 6. Annual average price of sweetcorn in Tokyo Metropolitan Central Wholesale Market from 2013 to 2017. Source: Agriculture & Livestock Industries Corporation (2018).

Year	2013	2014	2015	2016	2017	5-Year Average
Annual average price (yen per kg)	223	245	265	213	224	234

Table 7. Annual revenue per square meter from corn crops grown in different configurations.

	Configurations		
	Control	Low-Density	High-Density
Crop revenue (yen/m^2)	783.90	828.36	755.82

The revenue of power generation for different configurations is shown in Tables 4 and 5. The CHO Institute of Technology has secured the feed-in-tariff rate of 48 yen (approximately 0.44 USD) per kWh for 20 years. The annual revenue per square meter from PV power generation (S) can be calculated by

$$S\ [\text{yen/m}^2] = E \times r \tag{7}$$

where the annual power output per square meter of agrivoltaic PV modules is E (kWh) and r is the feed-in-tariff rate. Utilizing the corresponding values for each configuration, the annual revenue per square meter from PV power generation was 2855 JPY and 5710 JPY for the low-density and high-density configurations, respectively. Thus, the annual total revenue per square meter from corn crops and PV power generation ($V_c + S$) can be calculated as shown in Table 8.

Table 8. Annual total revenue per square meter from corn crops and PV in different configurations.

	Configurations		
	Control	**Low-Density**	**High-Density**
Total revenue (yen/m^2)	783.90	3683.36	6465.82

Therefore, if the annual revenues per square meter from corn crops in low-density and high-density configurations are $V_{\text{c(low)}}$ and $V_{\text{c(high)}}$, respectively, and those from PV power generation in low-density and high-density configurations are $S_{\text{(low)}}$ and $S_{\text{(high)}}$, respectively, their relationship with the annual revenue per square meter without agrivoltaic PV panels in the control configuration ($V_{\text{c(trad)}}$) can be described as

$$V_{\text{c(trad)}} < V_{\text{c(low)}} + S_{\text{(low)}} < V_{\text{c(high)}} + S_{\text{(high)}} \tag{8}$$

This relationship will not change even with a lower feed-in-tariff rate. Although the CHO Institute of Technology secured the feed-in-tariff rate of 48 yen per kWh in 2010, the rate has nonetheless been declining. Even with the lower feed-in-tariff rates, the annual revenue from PV power generation and the corn harvest in an agrivoltaic farm could be larger than that of a traditional corn field (Table 9).

Table 9. Annual total revenue per square meter with different feed-in-tariff rates.

Configuration	**Feed-In-Tariff Rates**			
	48	**26**	**11**	**8**
High-density	6465.82	3848.736667	2064.361667	1707.486667
Low-density	3683.36	2374.818333	1482.630833	1304.193333
Control	783.9	783.9	783.9	783.9

4. Discussion

This case study showed that it is possible to grow corn, a typical shade-intolerant crop, under the shade of agrivoltaic PV panels. The biomass of corn stover grown under PV module arrays spaced at 0.71 m intervals was no less than 96.9% that of corn without PV modules. Furthermore, the biomass of corn stover grown under PV module arrays spaced at 1.67 m intervals was even greater than that of corn without PV modules by 4.9%. In fact, the corn yield per square meter of the low-density configuration was 3.54 kg, which was larger not only than that of the high-density configuration, but also than that of the no-module control configuration by 5.6%.

This study also indicated that the annual revenue from PV power generation and the corn harvest in an agrivoltaic farm could be larger than that of a traditional corn field. Actually, the total revenue of the high-density configuration was 8.3 times larger than that of the control configuration, whereas that of the low-density configuration was 4.7 times larger.

4.1. Possible Reasons for High Crop Yield

Several factors may explain why incorporating PV panels into agriculture can be beneficial for crops. First, the light saturation point of each crop seems to be a key concept. Actually, only a small fraction of the incident sunlight is required for plants to reach their maximum rate of photosynthesis. As light intensity increases, a level is eventually reached where light is no longer the factor limiting the overall rate of photosynthesis. Just as a sponge becomes saturated with water, increasing the light no longer boosts photosynthesis after the light saturation point (Table 10).

Table 10. Light saturation points of selected crops [14].

Crops	Light Saturation Points (KLX)	Crops	Light Saturation Points (KLX)
Corn	80–90	Rice	40–45
Watermelon	80–90	Carrot	40
Tomato	80	Turnip	40
Taro	80	Sweet potato	30
Cucumber	55	Lettuce	25
Pumpkin	45	Green pepper	20–30
Blueberry	45	Spring onion	25
Cabbage	45	Mushroom	>20

Second, too much sunlight hinders crop growth. Daily exposure to harsh ultraviolet radiation can cause serious damage to plant DNA. In fact, plants have evolved mechanisms to protect themselves from sun damage; they produce special molecules and send them to the outer layer of their leaves to protect themselves. These molecules, called sinapate esters, block ultraviolet-B radiation from penetrating deeper into leaves [15].

Third, the shading caused by the PV panels reduces water evaporation. This is especially beneficial in the hot and dry season. It has been observed that shading results in water savings of 14–29% depending on the level of shade [16]. Also, PV panels reduce the diurnal variations in crop and soil temperatures, while the daily air temperature and vapor pressure deficits remain constant, even for the area located under the panels [4]. PV modules also alleviate soil erosion by reducing moisture evaporation [17].

4.2. Future Work

This research expanded the potential applications of agrivoltaic systems to shade-intolerant crops, but many crops have still not been evaluated for agrivoltaic applications. Future work is necessary to extend its use to shade-intolerant plants other than corn including watermelon, tomato, cucumber, pumpkin, cabbage, turnip, and rice. However, information on the shade-tolerance of crops remains limited. Therefore, as Dinesh and Pearce [11] reported, it is important to study the morphological traits of such crops to understand their behavior and light requirement patterns during different life stages from germination to harvest. Many different factors, i.e., radiation interception efficiency, light saturation point, damage from ultraviolet radiation, water evaporation, and crop temperature, potentially affect the shade tolerance of crops.

It should also be noted that this research only employed a limited number of samples. The case study was conducted at a small, 100 m^2 experimental farm with three configurations and only dozens of corn stalks in each configuration. While this case study showed that corn could grow well even under the shade of agrivoltaic PV panels, it is necessary to verify the reliability of these results with a larger sample size in future research. In addition, more studies on the financial feasibility of agrivoltaic systems should be conducted. The case of this study obtained a good return on the investment in the agrivoltaic system; however, it would be worthwhile to examine the financial feasibility of the system under many different assumptions with different installation costs and feed-in-tariff rates.

Furthermore, more advanced PV systems could be designed to improve the efficiency of electricity generation and reduce the impact on agricultural yields. For example, PV module tilt can be adjusted to enhance the power generation efficiency. One proposal involves an agrivoltaic system equipped with a programmed microcomputer and a motor that automatically adjusts the tilt to be perpendicular to the sun as it moves from east to west [18], solving the issue of fixed PV panels not fully converting solar energy to electricity. This problem can be solved by arranging PV panels to track the Sun. The proposed system may equip a programmed microcomputer and a motor that maintains the tilting of PV panels almost perpendicular to the Sun. In this way, maximum sunlight is incident on the panel at any time of the day, and thus the power generation efficiency can be improved. Additionally, bifacial PV panels could increase the electricity production per square meter of the PV module through the use of light absorption from the albedo [19]. Other ideas have been proposed to enhance crop productivity. Semi-transparent PV panels, which combine the benefits of visible light transparency and light-to-electricity conversion, could reduce shading on crops under agrivoltaic systems. In fact, semi-transparent PV panels have already been developed for greenhouse-roof applications [20]. PV panels with mirrored backings might also increase the availability of sunlight for crops by multiplying the reflection of incoming light to the ground. Further research is required to couple new PV panel technology to agrivoltaic systems.

Another area of research is the development of suitable PV modules for agrivoltaic systems. PV modules should be lightweight because they are mounted in high locations. The modules also need to be small to reduce the shadows cast on the ground as well as the influence of wind. As the output of modules for home use has been increasing, larger modules are becoming more popular; however, major manufacturers have not yet marketed modules of a suitable size and output for agrivoltaic systems. Also, the effect of dust spread by agricultural activity onto the PV panel surface on the power output of the system should be considered. Instead of periodically cleaning the PV modules, it could be possible to maintain optimum electricity output with a hydrophilic coating on the PV panel surface.

In addition, the question remains whether the revenue from agrivoltaic systems can equal the investment costs. In this research, the installation costs of the agrivoltaic system were not considered. The costs of PV systems, however, vary significantly among countries and even within a country because they are largely determined by local resource availability. It is important to confirm the financial feasibility of the system in a series of specific case studies.

5. Conclusions

Although existing studies have reported that agrivoltaics work well only for shade-tolerant crops, this research has shown that it could be possible to grow corn, a typical shade-intolerant crop, even under the shade of agrivoltaic PV panels. It was also indicated that an increase in the overall productivity of land could be achieved even with crops that require plenty of sunlight. This result implies that stilt-mounted agrivoltaic systems could be applicable a wider range of commercially important crops. If so, the practical availability of stilt-mounted agrivoltaic systems would be highly promising. This research should encourage more conventional farmers, clean energy producers, and policy makers to consider adopting stilt-mounted agrivoltaic systems. Particularly in densely populated regions, mountainous areas, and small inhabited islands, where land resources are relatively scarce, this system could simultaneously take advantage of limited land resources for both food and clean energy production.

It would be an exaggeration to claim that agrivoltaic systems could drive out other energy sources, but it is true that this system offers important advantages over fossil fuels as well as traditional PV systems. Limitations related to the installation area are one disadvantage of traditional PV power generation. This is less important for households, where PV modules installed on rooftops can generate sufficient electricity, but industry requires a huge area for PV power plants to provide a sufficient and constant electricity supply. As this research demonstrates, agrivoltaic systems can help to overcome the problem of limited land resources, negating this disadvantage of PV power generation.

Nevertheless, there are some disadvantages of agrivoltaic systems. Similar to traditional PV power generation, agrivoltaics cannot reliably generate constant energy; the system cannot adequately function if sunlight is not available during the night or on cloudy days. Thus, it is difficult to rely on agrivoltaic systems as a main power source even if the total generation capacity is large enough to meet a country's electricity demand. The key to solving this is to employ battery backup systems that can store electricity for use when sunlight is not available. Another issue affecting the expansion of PV generation, including agrivoltaics, is PV panel recycling. Although PV power generation itself does not cause pollution, the disposal of PV panels may have serious impacts on the environment. The impact could be particularly serious if agrivoltaic systems are adopted for large areas of farmland, resulting in huge volumes of PV panels requiring disposal. Thus, it is necessary to develop effective methods for recycling large volumes of PV panels while also promoting agrivoltaic systems.

Although the stilt-mounted PV system was originally developed to generate electricity from incoming sunlight on farmland, this system may also be an effective way to produce sustainable energy without devastating the environment. This system enables people to generate electricity on farmland, pasture land, water surfaces, roads, and anywhere people, animals, and plants are living. Moreover, even barren deserts can be changed into habitable lands where people can produce food and energy simultaneously with a system consisted of tilt-mounted PV modules installed at moderate intervals.

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