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RESEARCH ARTICLE

Rice yield and electricity production in agro-photovoltaic systems

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ABSTRACT

Fossil fuels, particularly oil, face sustainability challenges due to depletion and their role in increasing atmospheric CO_2 levels, contributing to climate change and impacting global agriculture. Renewable energy sources like solar power offer a viable alternative. This study explores the feasibility of agro-photovoltaic (APV) systems, which integrate solar panels with agricultural land to generate electricity while cultivating crops. Specifically, the impact of APV systems on rice production and quality was investigated. Solar modules with a total capacity of 99.84 kW were installed on a 2580 m^2 site, with two module configurations tested. Two rice (*Oryza sativa* L.) cultivars, Woonkwang and Saenuri, were transplanted and monitored for growth characteristics, chlorophyll content, and fluorescence, as well as yield and quality. Growth analysis of rice under APV systems showed minimal impact on plant height and tiller numbers, though chlorophyll content analysis indicated delayed leaf aging and extended maturation time. Rice yield decreased due to altered panicle and spikelet numbers. Quality analysis revealed changes in head rice rate and broken rice, stressing optimal harvest timing in APV systems. Shading conditions also affected physicochemical properties and taste profiles. Yields dropped by about 20% under APV systems, but the financial returns from electricity generation significantly outweighed the crop revenue loss. Despite the high initial installation costs and regulatory challenges, APV systems present a promising dual-use approach for enhancing farm income and promoting renewable energy. Continued research and investment are essential for optimizing APV systems and expanding their adoption.

Key words: Agro-photovoltaic (APV) systems, chlorophyll content, *Oryza sativa*, renewable energy, rice production, yield and quality.

INTRODUCTION

Fossil fuels, notably oil, have been the cornerstone of modern energy needs. However, their long-term use faces sustainability challenges, including the depletion of oil reserves expected within the next few decades and the role of fossil fuel consumption in increasing atmospheric carbon dioxide levels, a major contributor to climate change (Huang et al., 2015; Lawrence et al., 2018). The resulting climate shifts are anticipated to significantly impact global agriculture, not only in yield but also through the expansion of arid regions and alterations in cultivable land (Grigorieva et al., 2023).

To mitigate global warming induced by fossil fuels, the expansion of renewable energy sources is essential (Zhou et al., 2023). Solar energy, as a sustainable and abundant resource, is one of the promising alternatives, convertible into electricity via solar panels (Ukoba et al., 2024). However, installing solar panels in mountainous areas or on building rooftops faces ecological and regulatory challenges, respectively. In contrast, agricultural land presents a unique opportunity for solar power installation, where electricity generation and crop production can occur simultaneously. Agro-photovoltaic (APV) systems, therefore, offer a sustainable solution for expanding solar power generation without harming natural habitats. Recent research has actively explored the effects of solar panel shading on crop growth and yield (lettuce, potato, wheat) (Dinesh and Pearce, 2016; Trommsdorff et al., 2021).

The limitations of the APV system include high initial installation costs and the need for economic cost analysis. Additionally, for this reason and the blocked landscape, it will be a factor that discourages farmland owners. However, there is no doubt that the current global energy crisis and its increasing challenges can be solved using APV systems (Ghosh, 2023).

Sunlight is a crucial factor in plant photosynthesis and morphology, significantly influencing crop yield (Tang et al., 2022; Seyedi et al., 2023). Studies have shown that insufficient sunlight at various growth stages can hinder and delay rice growth (Fang et al., 2021; Ma et al., 2023), reduce film formation (Lee et al., 2016; Song et al., 2022), lower the ripening rate (Liu et al., 2014; Shang et al., 2024), and affect chlorophyll accumulation (Rezai et al., 2018), leading to significant yield declines.

The study revealed that shading conditions significantly impacted the lodging index of two rice varieties by reducing culm diameter, culm wall thickness, and increasing both plant and gravity center heights. Comparative analysis with the control indicated substantial reductions in cell wall components such as non-structural carbohydrates, sucrose, cellulose, and lignin (Wu et al., 2017).

However, the shading in APV systems is partial or temporary, and it remains unclear whether its effects differ from continuous shading. This necessitates research into the productivity and quality of crops under the specific shading conditions of APV systems. Therefore, this study aims to evaluate the feasibility of APV systems in promoting renewable energy, by analyzing changes in rice production and quality, alongside year-round electricity generation in an APV setup.

MATERIALS AND METHODS

Agro-photovoltaic systems installation and cultivation method

Solar modules, each with a capacity of 130 W, were installed on a 2580 m^2 site in Deokho-ri, Haimyeon, Goseong-gun, Gyeongsangnam-do, Republic of Korea. These modules were arranged in two configurations: A single module type (M1) and a double module type (M2). They were elevated 4 m above ground level, culminating in a total power generation capacity of 99.84 kW (Figure 1). Prior to transplanting rice (*Oryza sativa* L.), tillage and soil preparation were conducted in both the agro-photovoltaic (APV) system plots and the control plots. Transplanting involved two rice cultivars: Woonkwang, an early maturing type, and Saenuri, a mid-late maturing type. These were transplanted on 13 June, which was 20 d post-sowing, with a spacing of 30×15 cm and an average of three to four plants per hill. Fertilization across the site was standardized at 90 kg N, 45 kg phosphoric acid, and 57 kg K per hectare. The N application was split into 50% as basal dressing, 30% as top dressing at the tillering stage, and the remaining 20% at the panicle initiation stage. Phosphoric acid was applied entirely as basal dressing, while K was divided into 70% basal dressing and 30% top dressing at panicle initiation. The control area, where solar panels were not installed, was located adjacent to the area with solar panel installations, ensuring minimal variation in environmental conditions between the two zones. In the APV systems, rice plants were sampled at regular intervals, specifically focusing on the plants located in the center. The control group plants were also sampled at consistent intervals. To analyze rice yield and yield components, the sampling process was repeated three times.

Agricultural characteristics

The growth characteristics of rice in this study were examined according to the established standards of agricultural science and technology research (RDA, 2012). To monitor the changes in rice growth, plant height and tiller number were measured weekly following transplantation. The heading date was determined by observing the entire site and calculating the day when 40% of the total tillage reached the heading stage. Furthermore, key growth parameters such as plant height, panicle length, number of panicles, number of spikelets per panicle, percentage of ripened grains, and grain weight were thoroughly evaluated. The percentage of ripened grains was the number of ripened grains per hill divided by the total number of spikelets per hill.

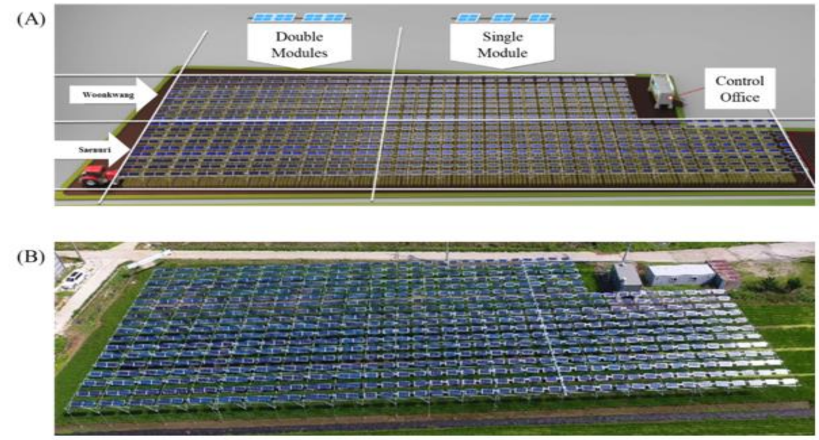

Figure 1. A model picture (A) and an actual installation picture (B) of the photovoltaic power generation system (99.84 kW). It was installed 4 m above the ground with single module type and double modules type. As for the rice cultivars, Woonkwang, an early-maturing, and Saenuri, a medium-late maturing, were transplanted.

Chlorophyll content and chlorophyll fluorescence analysis

In plant photosynthesis, the activity of photochemical reactions is closely tied to the amount of fluorescence emitted, with these reactions and fluorescence varying sensitively in response to external environmental conditions. To evaluate the stress induced by sunlight deficiency in the APV systems, we utilized a chlorophyll fluorescence response meter (OS30p+, Opti-Sciences, Hudson, New Hampshire, USA). Additionally, the chlorophyll content in leaves was assessed using the non-destructive chlorophyll content (mg m^{-2}) meter (CCM-300, Opti-Sciences) method.

Analysis of rice quality characteristics

Post-harvest, the rice was dried and polished to achieve a moisture content of 15%-16%. The quality of the polished white rice was determined using a rice grain inspection machine (Cervitec-1625, FOSS, Hillerød, Denmark), which categorized the rice into head rice, opaque rice, damaged rice, crack rice, and broken rice. Quality-related characteristics of the polished white rice, including whiteness, protein, and amylose content, were measured using a rice ingredient analyzer (Infratec-1241, FOSS). Additionally, the taste profile of the rice was analyzed with a rice taste tester (MA-90, Toyo Engineering Corp., Tokyo, Japan).

Statistical analysis

Statistical analyses were conducted to obtain the arithmetic mean and standard error, and the significance of differences among the treatment was evaluated using one-way ANOVA, complemented by Tukey's HSD test for significance levels of $p < 0.05$ and $p < 0.01$. These statistical procedures were performed using R software (version 4.0.2).

RESULTS AND DISCUSSION

Climate characteristics

The climatic conditions during the rice cultivation period in this study are illustrated in Figure 2. Specifically, the average monthly temperature throughout the rice cultivation period in 2017 was recorded at 22.3 °C. This figure is notably 0.7 °C higher than the average temperature of a typical year. Furthermore, the precipitation levels in 2017 were comparatively lower than the average, yet the total sunshine duration was observed to be 969.0 h. This duration surpasses the normal annual average by 134.2 h (normal year average: 834.8 h). Such climatic variations are hypothesized to positively influence not only rice cultivation but also the efficiency of solar power generation.

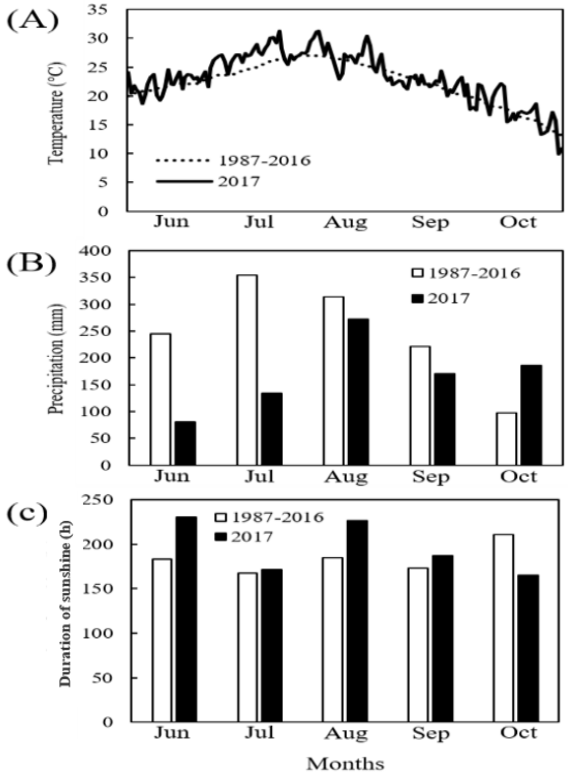

Figure 2. Comparison of the weather at the field where rice is growing with the average weather over the past 30 yr. (A) Average temperature, (B) precipitation, (C) sunshine duration.

Rice growth characteristics

Every 2 wk after transplanting, this study examined plant height and tiller number in two rice cultivars under the APV systems: Woonkwang and Saenuri. These cultivars were observed under two module conditions: A single module type (M1) and a double module type (M2). It was noted that there was nonsignificant difference in the plant height of 'Woonkwang' under the APV systems compared to the control (Figures 3 and 4). However, for 'Saenuri', plant heights were 68.9 cm in M1 and 70.3 cm in M2 within the APV systems, 5 wk after transplanting. These measurements are 6.0% and 8.2% higher, respectively, than the control group's plant height of 65 cm (Figures 3 and 4). This discrepancy persisted until the heading date, suggesting an impact from reduced sunlight exposure due to the APV systems.

Regarding tiller numbers, which significantly influence rice yield, Yoshida and Parao (1976) indicated that they are minimally affected by sunlight in the early vegetative stage but significantly influenced during the reproductive stage. This factor has a direct impact on rice yield. Consistent with this, the current study found nonsignificant difference in tiller numbers between the two rice cultivars in the APV systems compared to the control (Figure 4). This observation suggests that the reduced sunlight in the APV systems during the vegetative stage did not significantly affect the tiller number in rice.

Recent studies on APV systems and rice cultivation provide context for these findings. Scientists have investigated the economic viability of bifacial agrivoltaic projects for *O. sativa* in various countries. These studies focus on location-specific conditions, including solar irradiance and financing, to determine optimal configurations for rice production. Additionally, an analysis of rice yield under APV systems in Japan suggested that shading rates between 27% and 39% could maintain at least 80% of rice yield, emphasizing the potential of APV systems for efficient land use and sustainable energy generation (Gonocruz et al., 2021).

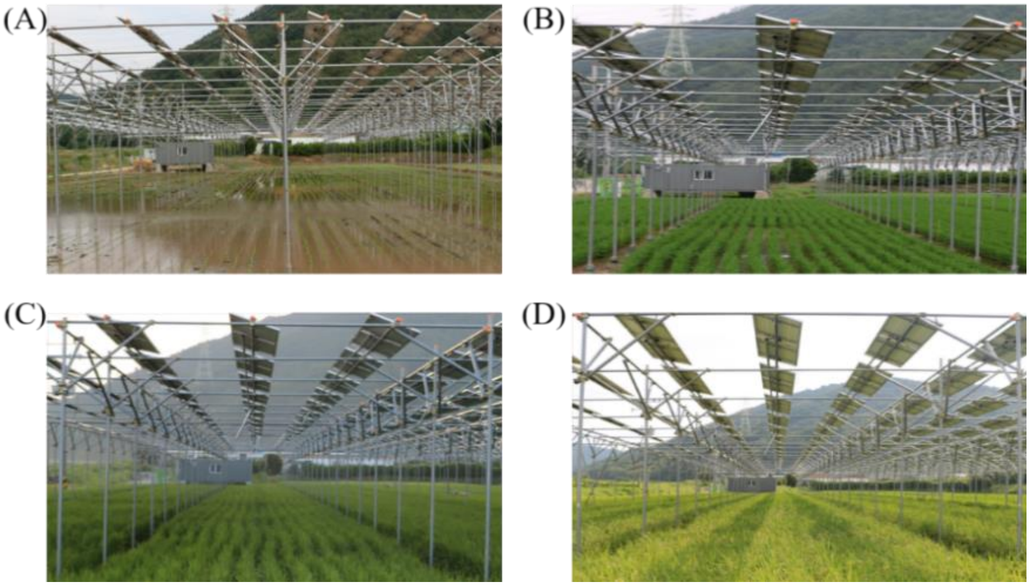

Figure 3. Rice growth site of agro-photovoltaic systems at experimental farm. (A) Early growth stage (immediately after transplanting); (B) vegetative growth stage (tillering stage); (C) reproductive growth stage (elongation stage); (D) ripening stage.

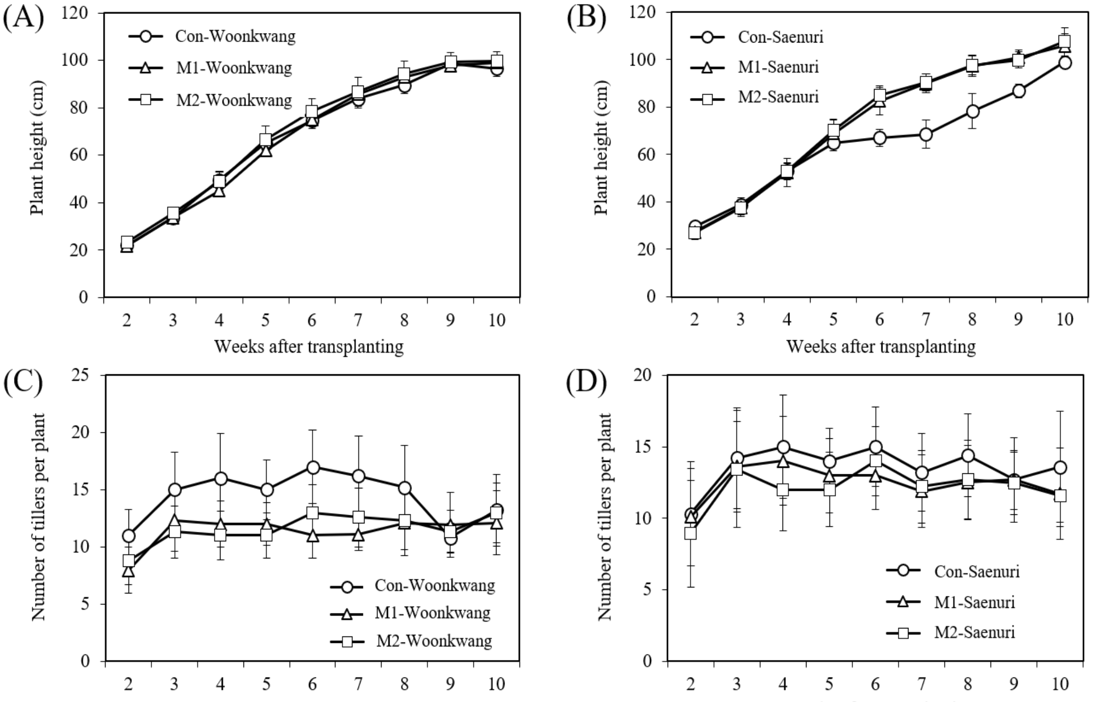

Figure 4. Change in rice height and tiller number of agro-photovoltaic systems. (A) Plant height of ‘Woonkwang’ (early maturing type); (B) plant height of ‘Saenuri’ (mid-late maturing type); (C) number of tillers of ‘Woonkwang’ (D); number of tillers of ‘Saenuri’. The data indicate the means ± SE (n = 20).

Chlorophyll content and fluorescence analysis

To understand the impact of reduced sunlight from solar power modules on late-stage rice growth, key fluorescence parameters like initial fluorescence yield (F_0), maximum fluorescence yield (F_m), photochemical efficiency (F_v/F_m), and photosynthetic performance (F_v/F_0) were measured (Wan et al., 2020). Seventeen weeks after planting, rice under solar modules showed higher chlorophyll content than the control, suggesting delayed leaf aging (Figure 5). Chlorophyll fluorescence analysis is used as an indicator for stress analysis. In general, it is known that when a plant is stressed, the F_0 value increases and the F_m value decreases, and these values differ depending on the chlorophyll content (Janeeshma et al., 2022).

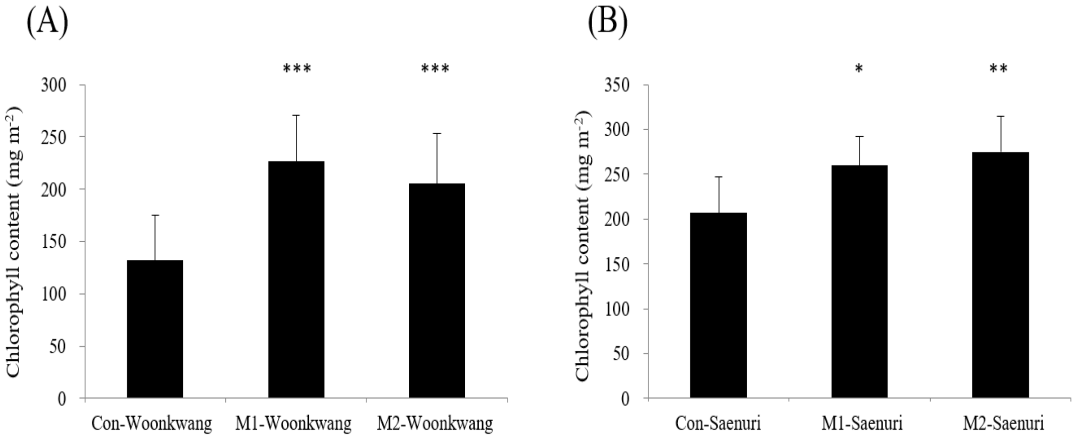

Figure 5. Chlorophyll content of rice 17 wk after transplanting in agro-photovoltaic system for two rice cultivars: Woonkwang (A) and Saenuri (B). The data indicate the means ± SE (n = 20). Asterisks indicate significant differences. *p value < 0.05; **p value < 0.01; ***p value < 0.001.

There was no difference in the variables of chlorophyll fluorescence of 'Woonkwang' in the early stages of heading between the APV systems and the control. However, as the harvest time approached, the chlorophyll content of 'Woonkwang' in the control decreased significantly compared to that in the APV systems. Accordingly, in chlorophyll fluorescence analysis, the F_0 and F_m values of 'Woonkwang' leaves in the control were lower than those of 'Woonkwang' leaves in the APV systems (Figure 6). Just before harvesting of 'Saenuri', the chlorophyll content of the leaves of 'Saenuri' in the control was lower than that of 'Saenuri' in the APV systems, and the F_0 and F_m values in the chlorophyll fluorescence reaction were correspondingly low (Figure 7). These results indicate that rice in APV system sites may need more time to mature fully due to reduced sunlight exposure.

Recent studies have corroborated the finding that shading markedly increases chlorophyll content in tea leaves. This increase has been attributed to the stimulation of chlorophyll synthesis genes, particularly those encoding protochlorophyllide oxidoreductase (CsPOR), as detailed in a study by Chen et al. (2021). Furthermore, both chlorophyll content and photosynthetic characteristics were found to be influenced by the extent of shading, with greater chlorophyll accumulation observed under more intense shading conditions (Sano et al., 2018; Yamashita et al., 2020).

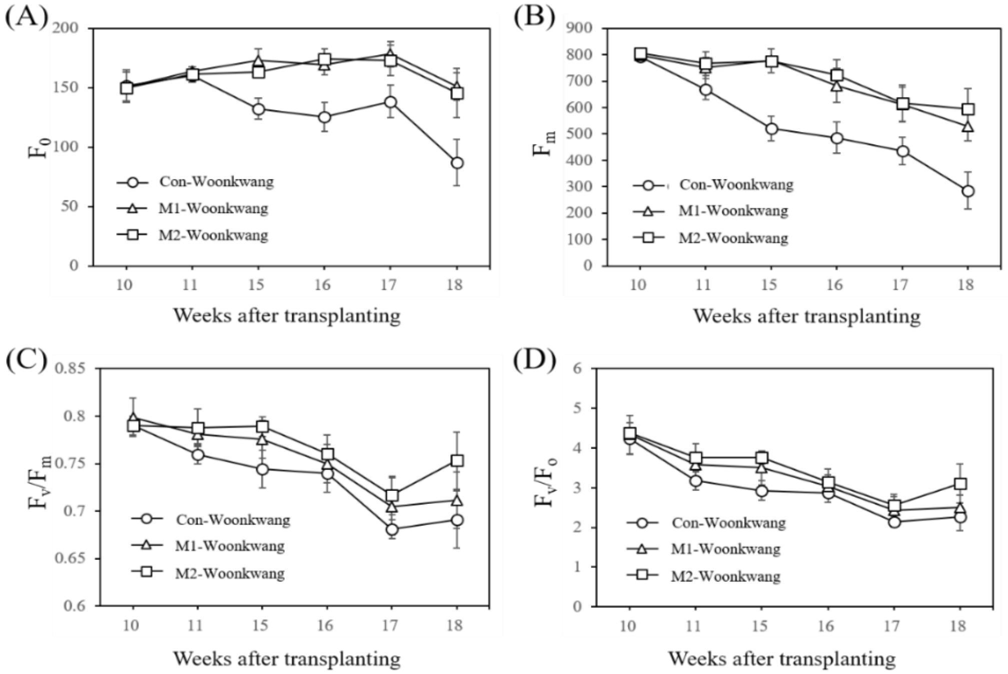

Figure 6. Changes in chlorophyll fluorescence parameters of 'Woonkwang' rice in agro-photovoltaic systems; initial fluorescence yield (F_0) (A); maximum fluorescence yield (F_m) (B); photochemical efficiency (F_v/F_m) (C); photosynthetic performance (F_v/F_0) (D). The data indicate the means ± SE (n = 20).

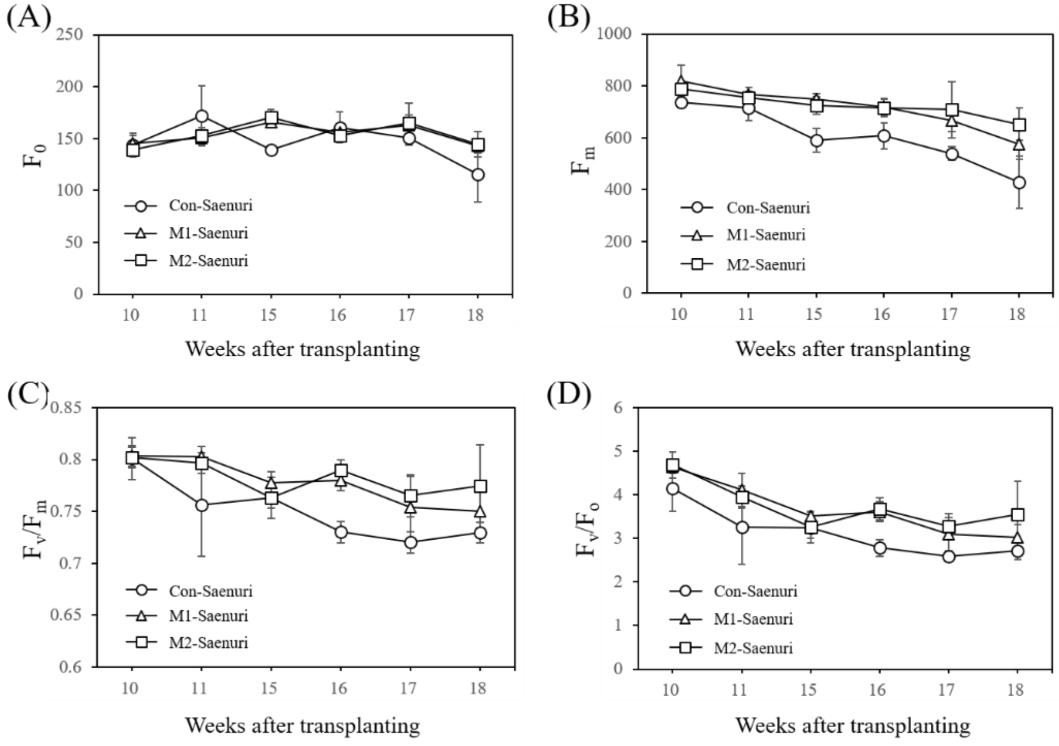

Figure 7. Changes in chlorophyll fluorescence parameters of 'Saenuri' rice in agro-photovoltaic systems; initial fluorescence yield (F_0) (A); maximum fluorescence yield (F_m) (B); photochemical efficiency (F_v/F_m) (C); photosynthetic performance (F_v/F_0) (D). The data indicate the means ± SE (n = 20).

Yield components and yield

Rice yield is influenced by the interaction between photosynthesis-derived anabolic products, their accumulation, and the assimilation pathways. Key factors include the source/sink ratio and environmental elements like temperature and sunlight (Lee et al., 2009). Solar radiation, crucial at various growth stages, has minimal impact during the vegetative stage but significantly affects spikelet numbers in the reproductive stage and grain yield during ripening (Yoshida, 1981).

In this study, yields of 'Woonkwang' and 'Saenuri' were measured in M1 and M2 regions under solar panels. Yield of 'Woonkwang' was 4448 (M1) and 452 kg ha^{-1} (M2), decreasing by 18.8% and 17.5% compared to the control (5479 kg ha^{-1}) (Table 1). 'Saenuri' showed similar trends with yields of 4719 (M1) and 4705 kg ha^{-1} (M2), a decrease of 15.0% and 15.3% compared to the control (5555 kg ha^{-1}) (Table 1). Light impacts spikelet filling and grain weight significantly (Chen et al., 2019). The number of panicles varied by cultivar and region, with 'Saenuri' showing a greater decrease in M1 and M2 compared to 'Woonkwang'. The number of spikelets per panicle was higher for 'Woonkwang' in the control, but the ripening rate was lower, balancing the yield decrease. For 'Saenuri', the control had fewer spikelets per panicle but a higher ripened grain ratio (Table 1).

A noteworthy finding of this study was the extended ripening period observed in regions M1 and M2 for 'Woonkwang', resulting in a harvest delay of approximately 2 wk compared to the control group. In contrast, 'Saenuri' was harvested in accordance with the control group's schedule, suggesting that the rice in regions M1 and M2 might not have fully matured. This discrepancy highlights the potential impact of environmental conditions, particularly sunlight, on the maturation process of rice.

Table 1. Variations of the rice yield and yield components in agro-photovoltaic systems. Different small letters within each column indicate significant differences at a p value < 0.05 to Tukey's test. Control: General open field without solar panels installed; M1: single module type; M2: double module type.

Treatments	Grains per panicle	Ripened grain rate	Thousand grain weight	Brown/rough rice ratio	Brown rice yield	Yield ratio
	Nr panicle^{-1}	%	g	%	kg ha^{-1}	%
Control-Woonkwang	109.0 ±7.9	68.3 ± 4.1	22.5 ±0.1	80.2 ± 0.1	5479 ± 99	100^{a}
M1-Woonkwang	85.2 ± 1.9	73.9 ± 4.9	23.5 ± 0.4	78.3 ± 0.1	4448 ± 102	81.2^{b}
M2-Woonkwang	87.1 ± 7.9	73.2 ± 0.1	24.0 ± 0.1	80.4 ± 0.1	4520 ± 114	82.5^{b}
Control-Saenuri	81.5 ± 4.5	93.4 ± 2.2	23.8 ± 0.4	82.7 ± 0.5	5555 ± 614	100^{a}
M1-Saenuri	113.0 ± 12.5	82.5 ± 6.5	24.0 ± 0.1	81.1 ± 0.9	4719 ± 152	85.0^{b}
M2-Saenuri	117.2 ± 18.4	85.4 ± 0.8	24.3 ± 0.4	81.3 ± 1.1	4705 ± 339	84.7^{b}

Rice quality

In rice cultivation, optimal harvest timing is crucial, as both early and late harvesting can decrease the percentage of head rice. In our study, 'Woonkwang' in the control showed a lower head rice rate and more broken rice compared to the M1 and M2 regions under the APV systems, largely due to a 2 wk delay in harvesting. This delay caused increased cracked rice, a result of moisture discrepancies during drying, which later turned into broken rice during milling (Table 2). Conversely, 'Saenuri' in the control had a higher head rice ratio than in the APV systems. Therefore, adjusting harvest times to align with the ripening stages is essential, especially under the APV systems (Table 2).

Additionally, the APV systems may cause delays in sowing times in double-cropping fields, potentially impacting growth and wintering rates. To mitigate these challenges, the adoption of early cultivation techniques, coupled with the selection of early-maturing rice varieties that are well-suited to APV system conditions, presents a viable approach. Continued research is necessary to identify the best rice cultivars for APV systems.

Table 2. Apparent rice quality in agro-photovoltaic systems. Different small letters within each column indicate significant differences at a p value < 0.05 to Tukey's test. Control: General open field without solar panels installed; M1: single module type; M2: double module type.

Treatments	Head rice	Broken rice	Opaque rice	Damaged rice	Heat-damaged rice
	%	%	%	%	%
Control-Woonkwang	52.4 ± 2.3^{a}	39.1 ± 0.1^{a}	7.3 ± 2.3	1.1 ± 0.0	0.3 ± 0.1
M1-Woonkwang	70.1 ± 2.6^{b}	25.2 ± 0.6^{b}	3.8 ± 1.3	0.8 ± 0.5	0.2 ± 0.1
M2-Woonkwang	69.7 ± 1.1^{b}	24.7 ± 0.1^{b}	4.6 ± 0.9	0.8 ± 0.0	0.3 ± 0.3
Control-Saenuri	95.0 ± 0.2	3.2 ± 0.1	1.5 ± 0.3^{a}	0.2 ± 0.0	0.0 ± 0.0
M1-Saenuri	89.4 ± 1.3	5.2 ± 0.1	5.2 ± 1.2^{b}	0.1 ± 0.0	0.1 ± 0.1
M2-Saenuri	91.3 ± 1.3	4.7 ± 1.1	3.9 ± 0.2^{b}	0.1 ± 0.1	0.0 ± 0.0

Physicochemical properties and taste of rice

Rice whiteness serves as a critical criterion for categorizing rice, with a standard value of 38 or higher considered optimal for taste (Goto et al., 2014). 'Woonkwang' in the control region exhibited slightly higher whiteness compared to those in M1 and M2 regions, albeit falling short of the preferred value of 38 (Table 3). Conversely, 'Saenuri' surpassed the standard, demonstrating a whiteness above 40 in the control, as well as M1 and M2 regions.

Table 3. Physicochemical properties and taste of rice in agro-photovoltaic systems. Different small letters within each column indicate significant differences at a p value < 0.05 to Tukey's test. Control: General open field without solar panels installed; M1: single module type; M2: double module type.

Treatments	Whiteness	Protein	Amylose	Toyo taste value
	%	%	%	
Control-Woonkwang	32.7 ± 0.1^{a}	6.1 ± 0.1	17.6 ± 0.2	54.0 ± 0.1
M1-Woonkwang	35.2 ± 1.6^{b}	7.6 ± 0.6	17.9 ± 0.6	52.0 ± 2.8
M2-Woonkwang	36.0 ± 0.3^{b}	7.4 ± 0.1	18.1 ± 0.1	54.5 ± 0.7
Control-Saenuri	40.7 ± 0.7	5.9 ± 0.4^{a}	21.2 ± 0.6	67.3 ± 3.5
M1-Saenuri	40.1 ± 0.1	6.5 ± 0.1^{b}	21.2 ± 0.1	64.0 ± 1.4
M2-Saenuri	40.3 ± 0.6	6.3 ± 0.1^{b}	21.2 ± 0.1	65.7 ± 2.1

From a dietary perspective, higher protein content is usually considered advantageous. However, in terms of rice palatability, it closely associates with the grain's stickiness and quality, hence the best quality rice is expected to have a protein content of 6.0% or less. The control 'Woonkwang' showed a protein content of 6.1%, lower than 'Woonkwang' from M1 (7.6%) and M2 (7.4%) regions, but not within the premium quality standard (Table 3). The control 'Saenuri' met the high-quality protein standard with a content of 5.9%, but the M1 and M2 variants displayed slightly higher protein content at 6.5% and 6.3%, respectively, failing to comply with the high-quality rice standard (Table 3).

The amylose content is another key factor influencing taste, as a high amylose content typically reduces the amylopectin content, increasing the cooked grain's volume while reducing its stickiness and increasing hardness, leading to diminished palatability (Shi et al., 2022). Amylose content may vary based on the rice cultivar and cultivation methodology (Han et al., 2018). No noticeable difference was observed between 'Woonkwang' and 'Saenuri' from M1, M2, and control regions in amylose content, although 'Woonkwang' demonstrated lower levels than 'Saenuri', a feature attributed to the intrinsic traits of the cultivar.

A technique involving the scanning of a unique electromagnetic wave onto the rice surface can predict the taste of rice by measuring the electromagnetic wave's reflectance and absorption rate, with the water retention film and gloss as considerations (Sim et al., 2017). Palatability was assessed using a rice taste measurement system (Kim et al., 2023). The palatability of 'Woonkwang' was consistent across the control and M1 and M2 regions. However, 'Saenuri's palatability was found to be lower in the M1 and M2 regions compared to the control region. 'Woonkwang's palatability was inferior to 'Saenuri's, considered a characteristic of the rice cultivar.

Electricity production of APV systems

This study evaluated an agricultural solar power system with a 99.84 kW capacity, using 768 modules, each 130 W, installed 4 m above ground. Monthly electricity production varied minimally, with the highest in April (14 466 kW h^{-1}) and the lowest in January (11 562 kW h^{-1}), showing only a 25% decrease in the latter (Figure 8). This demonstrates the system's effectiveness even in winter, particularly in southern Korea, known for favorable sunlight (Figures 2A, 2B). Such systems could significantly boost energy sales revenue in the region.

Further analysis revealed that the double module type in the APV systems was 15% more efficient than the single type, despite having a higher shading rate (32% for double *vs*. 28.6% for single) (data not shown). However, this increased shading did not significantly affect rice growth or yield. Therefore, the double module type is considered more economically efficient for power generation in APV systems. Continuous yearly analysis is recommended to fully assess these results, considering sunlight variability.

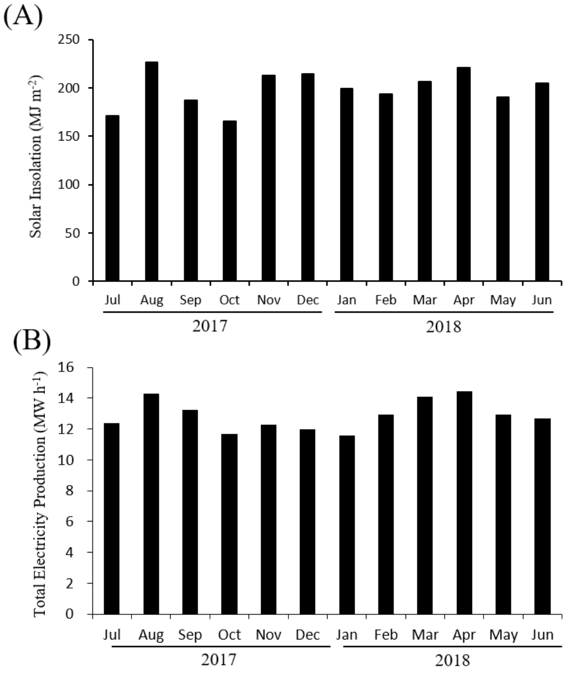

Figure 8. Annual solar insolation (A) and electricity generation amount (total of all solar modules at the research site) from agro-photovoltaic systems (B).

CONCLUSIONS

The agro-photovoltaic (APV) power generation is a system that integrates solar modules into farmland, enabling simultaneous crop cultivation and electricity production while preserving the agricultural land. By installing photovoltaic modules at a height suitable for agricultural machinery operation and arranging them with appropriate spacing, sufficient sunlight can be ensured for crops, thereby minimizing the decrease in rice yield. The APV represents an eco-friendly technology that concurrently produces electricity and harvests crops, thereby augmenting farmers' income. This dual-use approach offers a novel direction for the new and renewable energy sector by efficiently utilizing limited land resources. Despite the reduction in rice production by approximately 20% under APV systems compared to control areas, the financial returns from the electricity generated concurrently with rice cultivation are estimated to be about tenfold higher than those from rice alone. However, the initial cost of installing APV systems remains high, and implementation challenges, including licensing issues, persist. Nevertheless, an increase in demand for APV systems is likely to result in reduced solar power installation costs.

Author contribution

Conceptualization: J.S.C. Data curation: J.S.C. Formal analysis: J.S.C., S.W.P., S.M.Y., D.G.S. Methodology: J.S.C., J.J.L. Writing-original draft: J.S.C., S.W.P. Writing review && editing: J.S.C., J.J.L.

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