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Agrivoltaics in the Tropics: Soybean Yield Stability and Microclimate Buffering Across Wet and Dry Seasons

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Abstract

Agrivoltaics (APV) offers a promising dual land-use solution for food and energy production, yet empirical data regarding its impact on leguminous crops in tropical monsoon climates remain limited. This study evaluated the microclimate, growth, and yield of soybean (Glycine max) under an APV system compared to an open-field control during the wet and dry seasons in Bogor, Indonesia. The APV structure reduced incident solar radiation by approximately 35%, significantly lowering soil temperatures and maintaining higher soil moisture across both seasons. In the wet season, the APV treatment significantly increased grain yield (3528.8 vs. 1708.3 kg ha^{-1}, +106%) relative to the open field by mitigating excessive heat and radiative loads, which enhanced pod retention. In the dry season, APV maintained a yield advantage (2025.6 vs. 1724.4 kg ha^{-1}, +17%), driven by improved water conservation and a higher harvest index. Notably, shading did not delay phenological development or hinder vegetative growth in either season. These findings demonstrate that APV systems can contribute to sustainably higher yields and stability in tropical environments by buffering against season-specific environmental stresses, suggesting a viable pathway for sustainable agricultural intensification in equatorial regions.

Keywords: agrivoltaics; soybean; tropical monsoon climate; microclimate moderation; yield components; shade tolerance; sustainable agriculture

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Academic Editor: Giuseppe Ferrara

Received: 28 November 2025
Revised: 24 December 2025
Accepted: 30 December 2025
Published: 1 January 2026

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1. Introduction

Global agriculture is increasingly threatened by multiple interacting pressures, including rising heat and drought stress under climate change, the continuous decline of arable land, and escalating energy costs. Agrivoltaics (APV), a dual-use land system in which photovoltaic (PV) modules generate electricity while crops are grown beneath or between the panels, has been highlighted as a promising technology for sustainable agricultural transitions [1,2]. Previous studies have demonstrated that APV can moderate excessive solar radiation, reduce surface temperatures by 2–4 °C, and alleviate heat stress on crops, thereby maintaining or enhancing yield performance [1,2]. Furthermore, APV systems can produce approximately 150–300 MWh ha^{-1} of annual electricity while contributing to on-farm renewable energy supply [2,3]. By allowing simultaneous electricity generation and food production, APV increases land-use efficiency; Land Equivalent Ratio (LER) values of 1.2–1.7 have been reported, demonstrating more efficient land-use than monocropping

systems [2]. From a Food–Energy–Land nexus perspective, APV offers substantial potential to support climate-resilient and resource-efficient agricultural systems.

However, existing APV research is overwhelmingly concentrated in temperate regions such as Europe, North America, and East Asia, while empirical data from tropical monsoon climates—characterized by high temperature, high humidity, and reduced or variable light conditions—remain extremely limited [4–7]. Soybean (Glycine max), a globally important protein and feed crop, is highly sensitive to heat stress; temperatures above 33–36 °C during flowering and early pod formation suppress floral and microspore development, reduce pod set, inhibit seed filling, and consequently lower yield by 20–40% [8–10]. Despite this strong heat sensitivity, empirical studies evaluating how APV modifies soybean microclimate and the associated physiological responses, as inferred from changes in phenological development and productivity, under tropical monsoon conditions remain extremely limited, representing one of the most significant gaps in current APV research.

Bogor, located in West Java, Indonesia, exhibits a typical tropical monsoon (Am) climate with high mean annual temperatures (26–28 °C), substantial annual rainfall (3000–3500 mm), more than 270–300 rainy days per year, and consistently high relative humidity (>80%) [11–13]. Distinct wet (November–April) and dry (June–September) seasons lead to strong seasonal contrasts in solar radiation, rainfall, and temperature regimes. During the dry season, maximum temperatures rise to 32–34 °C and solar irradiance frequently reaches 500–600 W m^{-2}, conditions known to induce heat and light stress in soybean and contribute to reduced growth, pollen sterility, impaired seed development, and yield losses of up to 20–35% [8,14,15]. More than 90% of soybean cultivation in the Bogor region occurs in open-field systems [16,17], making the area highly suitable for evaluating APV-mediated microclimate modification and its potential to buffer soybean growth and yield against tropical stress conditions. Moreover, the Indonesian government has positioned APV as a key strategic technology to achieve its renewable energy target of 23% by 2025 and carbon neutrality by 2060 [4,5,18], further emphasizing the need for research on APV deployment in tropical climates.

Therefore, this study evaluated the microclimate (solar radiation, air temperature, soil temperature and moisture), growth traits, phenology, and yield components of soybean grown under APV and open-field conditions during one wet season and one dry season cropping cycle in Bogor, Indonesia. The objectives were to (1) quantify the effects of APV on soybean physiology, growth, and yield under tropical monsoon conditions, (2) assess the extent to which APV mitigates heat and radiation stress prevalent during the dry season, and (3) evaluate the potential of APV to stabilize soybean productivity amid increasing heat risks under climate change. By addressing the scarcity of empirical soybean–APV data from tropical regions, this study provides essential scientific evidence for expanding APV-based food–energy–land integration in low-latitude agricultural systems.

2. Materials and Methods

2.1. Study Area and Site Conditions

The field experiment was conducted at the Cikabayan Experimental Farm of IPB University, located in Bogor, West Java, Indonesia (6°33′08″ S, 106°43′00″ E; elevation 171 m). Two soybean (‘Detap-1’, a commonly used Indonesian variety) cropping cycles were implemented: the first during the wet season (January–March 2025) and the second during the dry season (July–September 2025). The study area is characterized by an Am climate with pronounced seasonal variability in rainfall, solar radiation, and temperature. It should be noted that the designation of dry season in this tropical environment refers to the period of lower average monthly rainfall, although substantial total rainfall may still occur, distinguishing it from temperate dry seasons.

The daily temperature and rainfall conditions during wet season (A) and dry season (B) cropping periods are presented in Figure 1. The wet season cultivation lasted 83 days, during which the mean, maximum, and minimum air temperatures were 25.9 °C, 34.0 °C, and 20.9 °C, respectively. Total rainfall amounted to 1272 mm, and rainfall events exceeding 1 mm occurred on 45 days. In contrast, the dry season cultivation spanned 79 days, with mean, maximum, and minimum temperatures of 26.1 °C, 35.4 °C, and 20.2 °C, respectively. Total rainfall during this period was 1087 mm, and only 28 days recorded more than 1 mm of precipitation. Notably, rainfall in the dry season was highly concentrated on a few specific days—such as 18 July (46.1 mm), 30 July (95.7 mm), 1 September (69.0 mm), and 28 September (54.2 mm)—while most other days were rainless, reflecting the distinct precipitation pattern characteristic of the dry season environment. This pattern, characterized by fewer rainy days and intermittent heavy downpours, is the defining feature of the dry season in this region, despite the high cumulative rainfall.

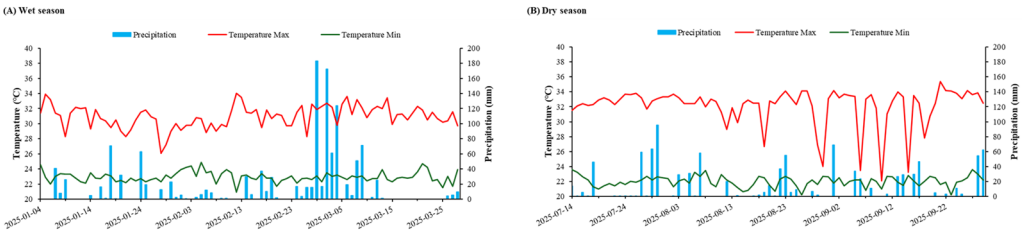


Figure 1. Daily maximum and minimum temperature and precipitation during the soybean growing season in Bogor, Indonesia, 2025.

Soils at the experimental site were classified as clay, with average texture values of 72.0% clay, 18.4% silt, and 9.6% sand within the sampled soil profile (0–50 cm). The soil was strongly acidic, with pH(H_2O) ranging from 4.0 to 4.8 and pH(KCl) from 4.1 to 4.6. Electrical conductivity was low (26.5–65.2 μS cm^{-1}), and organic carbon (1.28–2.24%) and total nitrogen (0.08–0.18%) were within moderate ranges. Cation exchange capacity (CEC) ranged from 15.98 to 23.95 $cmol_{(+)}$ kg^{-1}, while base saturation (12.5–30.1%) and available phosphorus (Bray I, 0.61–8.48 mg kg^{-1}) were low. Soil chemical properties were analyzed using depth-stratified soil samples collected at multiple depth intervals. Exchangeable K was also low (0.04–0.14 $cmol_{(+)}$ kg^{-1}). Exchangeable Ca and Mg were relatively higher in the surface layer but declined with depth.

2.2. APV System Configuration and Experiment Design

The experiment consisted of two treatments: (1) an APV plot equipped with an overhead solar structure and (2) an open-field control without any above-ground installations. Each plot measured 25 m × 12.5 m (312.5 m^2). Given the scale of the APV infrastructure, this study employed a single-plot-per-treatment design. Consequently, individual plant measurements were collected as subsamples within each treatment to assess variability, rather than serving as independent plot replications. Within each plot, eight crop rows were established. Soybeans were planted in double rows, with 50 cm between rows and 15 cm within rows, resulting in a target planting density of approximately 266,000 plants ha^{-1}. Identical planting density and row arrangement were applied to both the APV and open-field plots to ensure uniform crop distribution across treatments.

The APV structure installed in the treatment plot was mounted at a uniform height of 3.1 m above the ground, allowing unobstructed field operations and soybean cultivation beneath the panels. The clearance height of the APV structure was designed to allow routine field operations beneath the panels, although no heavy mechanized harvesting was conducted during the experimental period. The photovoltaic modules used in the system measured 2465 mm × 1134 mm and were installed at a fixed tilt angle of 15°. The

shading ratio, calculated based on the projected panel area and array configuration, was estimated at 34.9%. Detailed information on panel orientation, row spacing, and array layout is provided in Figure 2.

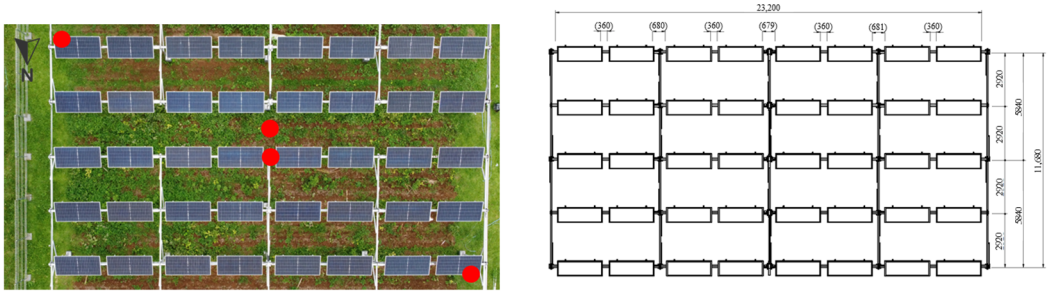


Figure 2. Layout of the agrivoltaic (APV) array, including panel orientation, row spacing, and structural configuration. Red points indicate the relative placement of microclimate sensors within the cultivated area.

2.3. Crop Management

Crop management practices were applied consistently across both the APV and open-field treatments and were maintained similarly during the two seasons cultivation cycles, except for differences in planting and harvesting dates. Soybean was established by direct seeding, with field planting conducted on 4 January 2025 for the wet season cycle and on 14 July 2025 for the dry season cycle. Two seeds were placed per planting hole at a depth of approximately 2–3 cm.

Prior to sowing, land preparation was carried out using a combination of mechanical and manual tillage to a depth of 20–30 cm (18–19 December 2024 for the wet season and 21 June 2025 for the dry season). Well-decomposed cow manure was applied as a basal amendment at a rate of 20 kg per furrow (27 December 2024 and 27 June 2025 for the wet and dry seasons, respectively) and incorporated into the top 10 cm of soil. Basal fertilization was applied at planting using granular compound fertilizer (500 g NPK plus 100 g KCl per furrow), followed by a second application five weeks after sowing with the same formulation and rate. The total nutrient input per cycle corresponded to approximately 80 g N, 80 g P_2O_5, and 180 g K_2O per furrow, with dolomite applied as a soil amendment to correct soil acidity.

Irrigation was uniformly administered to both treatments using a manual sprinkler system at a rate of approximately 15 L per furrow, three times per week, throughout both cropping cycles. Pest management was conducted using Matador 25 EC insecticide, applied once per cycle with a handheld sprayer to accommodate the limited clearance beneath the APV structure. Harvesting was performed manually at physiological maturity, on 28 March 2025 for the wet season crop and on 29 September 2025 for the dry season crop, to avoid interference from the overhead PV panels.

2.4. Microclimate Monitoring

Microclimatic conditions were continuously monitored throughout both cropping seasons to characterize the environmental factors influencing soybean growth and yield. An automatic weather station (RK900-01, Rika Sensors, Changsha, China) was installed to record atmospheric variables at 1 min intervals, including air temperature (°C), relative humidity (%), atmospheric pressure (hPa), and solar radiation (W m^{-2}). Subsurface variables—soil temperature (°C), volumetric water content (%), and soil electrical conductivity (dS m^{-1})—were also monitored. In the open-field control plot, an additional rainfall sensor was installed to quantify precipitation (mm) during both cropping seasons, while effective rainfall beneath the APV system was not directly measured.

A total of five monitoring points were established: four located directly beneath the APV structure at representative positions between panel rows (at the northwest and southeast corners and two central positions beneath the panel rows) to capture spatial variability, and one positioned 2 m outside the structure to represent open-field conditions. Atmospheric sensors were mounted at a height of 1.5 m above ground level, while soil sensors were installed at a depth of 15–20 cm.

To evaluate the overall microclimatic differences, data from the four under-panel monitoring points were averaged to represent the APV condition. Subsequently, daily mean values for both the APV and open-field treatments were calculated and used for all statistical comparisons.

2.5. Plant Growth and Yield Measurements

Soybean growth and yield traits were assessed during both the wet season and dry season experiments under the APV and open-field control treatments. Plants were randomly selected within each plot, with 24 plants sampled from the APV treatment (12 directly beneath the panels and 12 between panel rows) and 12 plants from the open-field control. Because no significant differences were detected between plants located directly under the panels and those between panel rows ($p > 0.05$), the mean of the two positions was used as the representative value for the APV treatment.

Phenological development was evaluated using the criteria of [19], focusing on the R1 (begin flowering), R3 (begin pod formation), and R5 (begin seed filling) stages. These stages correspond to the period during which most soybean yield components are determined and are widely used as key checkpoints in soybean growth analysis [20,21]. All weight measurements were taken using mechanical scales (CAMRY 30 kg, Zhongshan Camry Electronic Co., Ltd., Zhongshan, China; FIVE GOATS 10 kg, Guangzhou Wuyang Scale Factory, Guangzhou, China) and an electronic scale (FLECO F-111, PT. Fleco Indonesia Electronics, Jakarta, Indonesia).

2.5.1. Wet Season

Plant growth and yield measurements were collected twice weekly from 4 weeks after sowing until harvest. The following variables were recorded:

- Vegetative growth traits: plant height (cm) and number of nodes.
- Phenology: days to R1, R3, and R5.
- Yield components: grain yield (kg ha^{-1}), number of pods per plant, number of seeds per pod, number of seeds per plant, 100 seed weight (g), seed weight per plant (g), and aboveground biomass (g plant^{-1}).

These traits collectively capture 70–90% of soybean yield variation and are recognized as key determinants of final grain yield [20,22,23].

2.5.2. Dry Season

During the dry season, plant measurements were streamlined to focus on yield-related variables most sensitive to microclimatic differences. Previous studies have shown that certain yield components, such as seeds per pod, display limited variability across environments and contribute minimally to yield differentiation [21,24]. In contrast, traits such as pods per plant, 100-seed weight, seed weight per plant, and biomass are repeatedly reported as primary determinants of soybean grain yield [22–24]. Accordingly, only essential variables were retained. However, vegetative growth traits were measured consistently with the wet season.

Measurements were collected weekly from 7 days after sowing until harvest, and included the following:

- Vegetative growth traits: plant height (cm) and number of nodes.
- Phenology: days to R1, R3 (R5 progression was inferred through direct yield measurements at maturity).
- Yield components: grain yield (kg ha^{-1}), number of pods per plant, 100 seed weight (g), seed weight per plant (g), and aboveground biomass (g plant^{-1}).

This streamlined measurement protocol improved field efficiency under dry season conditions while maintaining the capacity to accurately evaluate plant growth and yield responses.

Grain yield (kg ha^{-1}) was estimated by upscaling plant-level seed yield to the target planting density. Specifically, grain yield was calculated as

$$\text{Grain yield}\left(\text{kg ha}^{-1}\right) = \left(\text{seed weight per plant} \times \text{planting density}\left(\text{plants ha}^{-1}\right)\right)/1000$$

The harvest index (HI, %) was calculated as

$$\text{HI}(\%) = \left(\frac{\text{seed weight per plant}}{\text{aboveground biomass per plant}}\right) \times 100$$

Both seed and aboveground biomass weights were recorded immediately after harvest under the same moisture conditions, and no moisture content adjustment was applied in the calculation of HI.

2.6. Statistical Analysis

All microclimate and plant measurement datasets were pre-processed in Microsoft Excel 2021, including the removal of missing values and the calculation of means and standard deviations. To evaluate treatment effects between the APV and open-field conditions, independent two-tailed *t*-tests were performed using JMP® version 17.0 (SAS Institute Inc., Cary, NC, USA). Prior to analysis, tests for homogeneity of variance were conducted to verify the assumption of equal variances. However, given the single-plot-per-treatment design, these statistical comparisons should be interpreted as exploratory, reflecting within-plot variability rather than true plot-level replication. Statistical significance was assessed at the 1% and 5% levels, and the following notations were used to indicate significance in tables and figures: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, and n.s. (not significant).

3. Results

3.1. Microclimate Modifications Under the APV System

Microclimatic conditions observed under the APV structure and the open-field control during the wet and dry soybean cultivation seasons are presented in Table 1. Solar radiation was the most significantly affected variable, consistently lower beneath the APV structure than in the open field across both seasons ($p < 0.001$). The reduction rates were approximately 33.9% in the wet season and 37.4% in the dry season, confirming that the PV modules effectively intercepted incident light [25,26].

Contrary to the expectation of a cooling effect on the air, the maximum air temperature was significantly higher under the APV structure in both seasons ($p < 0.001$). Atmospheric pressure and EC also showed statistically significant differences between treatments ($p < 0.001$), although the absolute magnitudes of these differences were relatively small. In contrast, soil temperature and moisture exhibited distinct responses to shading, with the APV system consistently maintaining lower soil temperatures and higher moisture levels ($p < 0.001$), demonstrating that the system modifies the ground-level microclimate through altered radiative and evaporative processes.

Table 1. Seasonal microclimate characteristics under agrivoltaic (APV) and open-field conditions during wet and dry season soybean cultivation.

Variable	Wet Season			Dry Season		
	APV	Open Field	Significance [1]	APV	Open Field	Significance [1]
	Mean ± SD	Mean ± SD		Mean ± SD	Mean ± SD	
Temperature (°C)	26.0 ± 0.8	26.0 ± 0.7	n.s.	26.3 ± 0.9	26.2 ± 0.9	n.s.
Maximum temperature (°C)	32.1 ± 1.9	31.2 ± 1.6	***	34.0 ± 1.7	32.6 ± 1.3	***
Minimum temperature (°C)	22.8 ± 0.7	23.0 ± 0.7	*	21.8 ± 0.8	22.1 ± 0.8	n.s.
Soil temperature (°C)	27.6 ± 0.5	28.4 ± 0.6	***	27.5 ± 0.6	28.5 ± 0.6	***
Maximum soil temperature (°C)	28.5 ± 0.7	28.8 ± 0.6	*	28.9 ± 0.7	29.0 ± 0.6	n.s.
Minimum soil temperature (°C)	26.8 ± 0.5	28.0 ± 0.5	***	26.3 ± 0.6	27.6 ± 1.1	***
Relative humidity (%)	97 ± 3	100 ± 2	***	94 ± 4	98 ± 2	***
Soil moisture (%)	27.3 ± 1.9	25.0 ± 1.7	***	29.6 ± 1.9	27.9 ± 1.9	***
Electrical conductivity (dS m^{-1})	0.165 ± 0.021	0.074 ± 0.008	***	0.188 ± 0.019	0.081 ± 0.006	***
Air pressure (hPa)	990 ± 3	989 ± 1	***	991 ± 1	990 ± 1	***
Solar radiation (W m^{-2})	193.3 ± 51.9	292.3 ± 74.4	***	242.9 ± 42.6	388.5 ± 76.0	***

[1] Statistical differences between APV and open-field treatments were assessed using independent *t*-tests (n.s., $p \geq 0.05$; * $p < 0.05$; *** $p < 0.001$). Values represent means ± standard deviations (SD).

3.1.1. Microclimate Characteristics During the Wet Season

During the wet season, the APV system significantly modified both atmospheric and soil microclimatic conditions compared to the open field (Table 1).

Solar radiation was significantly reduced under the APV system (193.3 ± 51.9 W m^{-2}) relative to the open field (292.3 ± 74.4 W m^{-2}, $p < 0.001$). This approximately 34% reduction in solar radiation under the APV system was consistent with partial-shading patterns reported in previous APV microclimate studies [25,26].

Air temperature exhibited contrasting responses between treatments. Maximum air temperature was slightly but significantly higher under the APV system (32.1 °C) than in the open field (31.2 °C, $p < 0.001$), whereas minimum air temperature was significantly lower under APV conditions (22.8 °C vs. 23.0 °C, $p = 0.010$).

Soil thermal conditions differed markedly between treatments. Mean soil temperature was significantly lower under the APV system (27.6 ± 0.5 °C) compared to the open field (28.4 ± 0.6 °C; $p < 0.001$), with both maximum and minimum soil temperatures showing similar trends. Soil volumetric water content was significantly higher under the APV system (27.3 ± 1.9%) than in the open field (25.0 ± 1.7%, $p < 0.001$). Higher soil moisture under the APV system was consistently observed during the wet season, accompanied by reduced evaporative losses and prolonged soil water availability following rainfall events, in line with observations reported for APV systems in humid climates [3,27]. Electrical conductivity was also significantly higher under APV conditions ($p < 0.001$).

3.1.2. Microclimate Characteristics During the Dry Season

During the dry season, microclimatic differences between the APV and open-field treatments became more pronounced, particularly with respect to thermal conditions and soil water status (Table 1).

Maximum air temperature was significantly higher under the APV structure (34.0 ± 1.7 °C) than in the open field (32.6 ± 1.3 °C, $p < 0.001$), while minimum air temperature did not differ significantly between treatments ($p = 0.058$). The consistently higher daytime air temperature observed beneath the APV structure coincided with reduced wind exposure and constrained airflow beneath the panel array, a pattern also reported in previous APV microclimate observations [28].

Soil temperature responses showed a clear buffering effect under the APV system. Mean soil temperature was significantly lower under APV conditions (27.5 ± 0.6 °C) com-

pared to the open field (28.5 ± 0.6 °C, $p < 0.001$). Minimum soil temperature was likewise significantly reduced under APV shading (26.3 °C vs. 27.6 °C, $p < 0.001$), whereas maximum soil temperature was numerically lower but not statistically different between treatments ($p = 0.362$). Collectively, these results demonstrate reduced soil heat accumulation and a narrower diurnal soil temperature range under APV shading, consistent with microclimate buffering effects reported across both temperate and tropical APV systems [25,26].

Soil volumetric water content during the dry season remained significantly higher under the APV system (29.6 ± 1.9%) than in the open field (27.9 ± 1.9%, $p < 0.001$). This sustained difference was observed throughout the measurement period, indicating reduced soil water depletion under APV conditions during periods of limited and temporally concentrated rainfall [3,27]. Solar radiation followed a similar pattern to the wet season, with significantly lower mean values recorded under the APV structure (242.9 W m^{-2}) compared to the open field (388.5 W m^{-2}, $p = 0.002$).

3.1.3. Integrated Microclimate Responses and Implications

Across both seasons, the microclimate responses beneath the APV structure followed a consistent pattern. The reduction in solar radiation induced by the PV modules led to lower soil temperatures, which in turn suppressed soil evaporation, resulting in significantly higher soil moisture levels. This pattern illustrates the core mechanism through which APV systems buffer hydrological stress [3,26,27].

However, contrary to some previous studies suggesting a cooling effect on ambient air, our results showed significantly higher maximum air temperatures under the panels in both seasons ($p < 0.001$). This suggests that under the specific climatic conditions of this study (tropical monsoon), the APV structure may have restricted airflow, leading to localized heat retention [28,29]. These findings highlight the importance of optimizing structural design—such as increasing panel height or spacing—to enhance ventilation and prevent heat stress in future APV installations.

Overall, the APV system reduced solar radiation by approximately 34–37%, lowered average soil temperatures by roughly 1 °C, and maintained significantly higher soil moisture, providing a distinct microenvironment for soybean cultivation.

3.2. Soybean Growth, Phenology, and Yield Responses

3.2.1. Phenological Development

The comparison of phenological development between treatments revealed that APV installation did not delay the progression of soybean growth stages in either the wet or dry season (Figure 3). During the wet season, the days to reach R1, R3, and R5 under the APV structure were 38.3, 47.7, and 52.9 days, respectively, which were statistically indistinguishable from the open-field control ($p > 0.05$). These findings demonstrate that partial shading of approximately 35% did not disrupt the transition to reproductive growth.

In the dry season, overall phenological progression occurred earlier than in the wet season (e.g., R1 at 32 days), reflecting the influence of higher temperature and solar radiation on developmental rates. The timing of R1 and R3 under APV and open-field conditions was nearly identical, with only a minor difference observed for R3 ($p = 0.02$). However, the magnitude of this difference (0.8 days) was too small to indicate any biologically meaningful delay, suggesting that APV-induced shading did not impede phenological progression even under high-temperature, high-radiation conditions.

These results align with previous reports that soybean reproductive development is governed primarily by temperature, photoperiod, and thermal time, rather than by moderate reductions in light intensity. Refs. [19,30] emphasized that transitions from R1 to R5 are largely regulated by accumulated heat units and endogenous physiological signals.

Likewise, environmental studies have shown that reproductive development is relatively stable across varying light environments when temperature and photoperiod requirements are met [25,31].

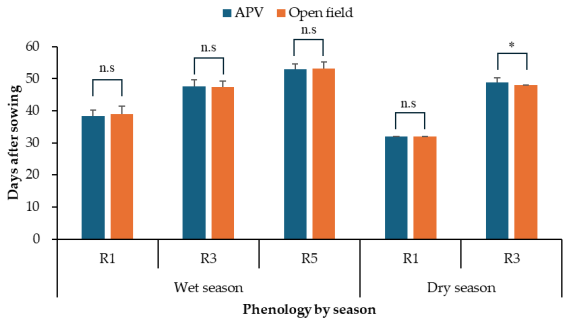


Figure 3. Phenological development (R1–R5) of soybean under agrivoltaic (APV) and open-field conditions during the wet and dry seasons. Bars indicate mean ± SD. Asterisks denote significant differences between treatments (* $p < 0.05$), and n.s. indicates non-significant differences.

Importantly, despite a 30–35% reduction in incoming solar radiation beneath the APV array, no delay in R1–R5 progression was detected in this study. This provides experimental evidence that APV systems do not impose negative physiological constraints on soybean reproductive development in tropical monsoon climates.

While the R5 stage was not assessed during the dry season cycle, the analysis of final yield components provides sufficient data to evaluate crop productivity. Therefore, the absence of this intermediate stage does not significantly impact the overall interpretation of the results. (1) The reproductive stages from R5 to R7 are strongly correlated with yield components such as pod number, seed weight, and thousand-seed weight; therefore, direct measurement of these components can fully compensate for the omission of R5 [32,33]. (2) Numerous international soybean field studies adopt a simplified phenological protocol focusing on R1 and R3 due to field constraints, with validated accuracy for interpreting growth and yield responses [30,31].

Therefore, the combined phenological dataset collected in this study (R1 and R3) in both seasons, plus R5 in the wet season together with final yield components, provides scientifically sufficient information to interpret soybean physiological responses and yield formation under APV and open-field conditions.

3.2.2. Vegetative Growth Characteristics

Across both seasons, plant height exhibited either greater or comparable values under the APV system relative to the open-field control, indicating that the approximately 35% reduction in solar radiation did not induce vegetative growth delays (Figure 4). In the wet season, APV plants showed significantly greater height from 4 weeks after sowing (WAS) onward (37.4 vs. 28.8 cm, $p < 0.001$), and this difference persisted during the mid–reproductive period (e.g., 8 WAS: 82.5 vs. 62.3 cm, $p < 0.001$). Although final height at 12 WAS was higher under APV (108.0 vs. 82.2 cm), the increased variance resulted in a non-significant difference.

In the dry season, early-stage differences were again evident; no difference was observed at 1 WAS, but APV plants were significantly taller at 2–3 WAS (e.g., 2 WAS: 17.6 vs. 13.3 cm, $p < 0.01$). As the season progressed, the difference diminished and became non-significant during the late vegetative phase.

These patterns align with established physiological principles showing that moderate shade reduces excessive light and heat stress, thereby stabilizing early canopy development without suppressing overall vegetative growth [25]. Furthermore, soybean stem elongation

is primarily regulated by thermal time, photoperiod, and genotypic controls rather than absolute irradiance levels [19,30,31]. Thus, the consistently non-delayed height development across seasons confirms that APV shading did not hinder vegetative progression and, under certain conditions, even enhanced early growth.

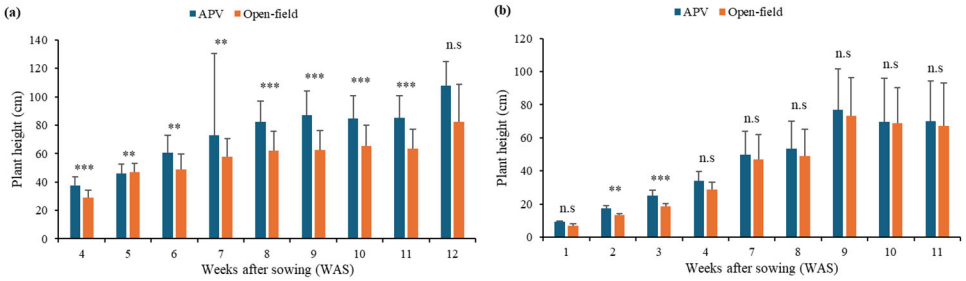


Figure 4. (**a**) Wet season and (**b**) dry season plant height measured under agrivoltaic (APV, blue bars) and open-field (orange bars) conditions. Data are presented as mean ± SD. Statistical differences between treatments at each sampling time were evaluated using an independent two-sample *t*-test, with significance levels indicated as ** $p < 0.01$, *** $p < 0.001$, n.s. = not significant.

Node development showed similar seasonal patterns and was not negatively affected by APV shading (Figure 5). In the wet season, node number did not differ significantly between treatments at any sampling time ($p > 0.05$), despite occasional higher mean values under APV (e.g., 8 WAS: 23.7 vs. 16.0 nodes). In the dry season, node number increased steadily under both treatments, and no statistically significant differences were observed throughout the season, even when APV plants displayed slightly higher averages at several sampling points (e.g., 8 WAS: 17.0 vs. 12.9 nodes).

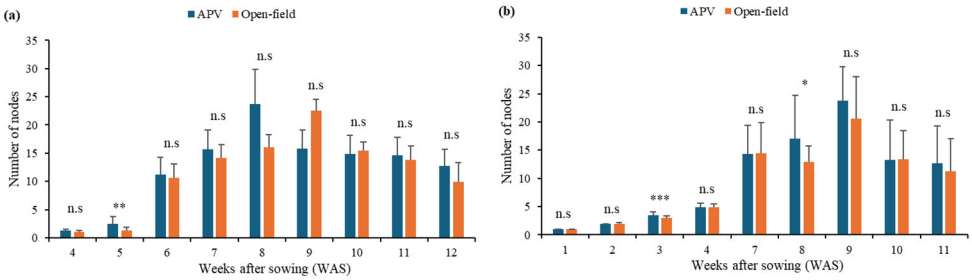


Figure 5. (**a**) Wet season and (**b**) dry season number of nodes measured under agrivoltaic (APV, blue bars) and open-field (orange bars) conditions. Data are presented as mean ± SD. Statistical differences between treatments at each sampling time were evaluated using an independent two-sample *t*-test, with significance levels indicated as * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, n.s. = not significant.

The observed stability in node development across seasons is consistent with the understanding that node addition rate is strongly driven by thermal time accumulation and developmental signaling and is only weakly affected by moderate reductions in irradiance [19,30]. Moreover, international APV field trials have demonstrated that 20–40% shading does not delay node formation in soybean or other C3 crops [25].

Given that node number is a key determinant of reproductive potential and is strongly correlated with yield components such as pod number and seeds per plant [31–33], the absence of treatment differences indicates that APV did not disrupt the structural basis of yield formation.

3.2.3. Yield Components and Final Yield

Across both the wet and dry seasons, the APV treatment maintained or improved soybean yield relative to the open-field control. The magnitude and direction of these

responses were closely associated with season-specific microclimate modifications and changes in key yield components (Table 2).

Table 2. Yield components and final grain yield of soybean under agrivoltaic (APV) and open-field conditions during the wet and dry seasons.

Variable	Wet Season			Dry Season		
	APV	Open Field	Significance [1]	APV	Open Field	Significance [1]
	Mean ± SD	Mean ± SD		Mean ± SD	Mean ± SD	
Number of pods per plant	70.9 ± 29.1	44.8 ± 18.2	**	34.9 ± 16.0	33.7 ± 19.2	n.s.
Number of seeds per pod	2.3 ± 0.7	2.2 ± 0.3	**	-	-	-
Number of seeds per plant	156.0 ± 62.6	99.0 ± 43.9	n.s.	-	-	-
Weight Seed (g plant^{-1})	46.5 ± 16.5	26.5 ± 13.4	***	30.3 ± 11.7	24.7 ± 8.1	n.s.
Aboveground biomass (g plant^{-1})	107.7 ± 37.3	63.2 ± 32.8	**	82.3 ± 19.1	81.9 ± 24.5	n.s.
100 seed weight (g)	37.0 ± 0.0	30.0 ± 0.0	***	29.0 ± 4.1	28.0 ± 2.6	n.s.
Grain yield (kg/ha)	3528.8 ± 192.3	1708.3 ± 243.6	***	2025.6 ± 452.9	1724.4 ± 316.3	n.s.
Harvest Index (%)	43.3 ± 4.4	44.1 ± 9.0	n.s.	36.2 ± 10.1	30.3 ± 5.1	*

[1] Statistical differences between APV and open-field treatments were assessed using independent *t*-tests (n.s., $p \geq 0.05$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$). Values represent means ± standard deviations (SD). And - indicates data were not collected for this specific season.

In the wet season, the APV plot exhibited markedly higher values across almost all yield attributes compared to the open-field plot. Specifically, the number of pods per plant was significantly higher under the APV system (70.9 ± 29.1) than in the open field (44.8 ± 18.2) ($p < 0.001$). This reproductive success was supported by vigorous vegetative growth, as reflected in the significantly greater aboveground biomass (107.7 vs. 63.2 g, $p = 0.001$) in the APV plot.

Consequently, final yield components showed substantial improvements under shading. Seed weight per plant was significantly higher in the APV plot (46.5 g) compared to the open field (26.5 g) ($p = 0.001$). Although the increase in the number of seeds per pod was small in magnitude (2.3 vs. 2.2 seeds pod^{-1}), it was statistically significant ($p < 0.01$). In contrast, the total number of seeds per plant was numerically higher under APV conditions (156 vs. 99), but the difference was not statistically significant ($p > 0.05$). Other yield metrics, including 100-seed weight (37.0 vs. 30.0 g) and final grain yield (3528.8 vs. 1708.3 kg ha^{-1}), were significantly higher in the APV plot than in the open field ($p < 0.001$).

These results align with the classical understanding that pod number strongly determines the number of seeds produced per plant and, consequently, final yield [32]. The simultaneous increases in aboveground biomass and pod number suggest that the APV microclimate supported sustained growth, providing the necessary photosynthates for pod filling. Board and Kahlon [33] demonstrated that increases in pod number are typically followed by proportional increases in seed number and weight, a physiological pattern clearly replicated in our wet season results.

In the dry season, the effect of APV was more moderate but remained positive. The APV plot produced numerically more pods per plant (34.9 vs. 33.7) and greater seed weight per plant (30.3 vs. 24.7 g), alongside a marginally higher 100-seed weight (29.0 vs. 28.0 g). While aboveground biomass was comparable between treatments (82.3 vs. 81.9 g), the final grain yield under the APV system exceeded that of the open field by approximately 17% (2025.6 vs. 1724.4 kg ha^{-1}). Notably, the HI was higher in the APV plot (36.2% vs. 30.3%, $p < 0.05$), indicating a more efficient allocation of assimilates to reproductive organs. Reference [34] similarly emphasized that under water-limited or thermally stressful conditions, the efficiency of assimilate partitioning becomes a major determinant of final yield, which aligns with the dry season APV response observed here.

Taken together, the yield responses across both seasons reflect a coherent yield-formation pathway. Increases in pod number were consistently associated with increases in seed number per plant, which in turn contributed to greater seed weight and ultimately higher grain yield. Importantly, these yield component shifts were tightly coupled with microclimate modifications. During the wet season, shading enhanced yield by moderating excessive radiation and promoting both biomass accumulation and pod development [35]. In the dry season, APV shading stabilized yield by improving physiological allocation efficiency (HI) under high-temperature conditions. These findings demonstrate that APV systems can enhance soybean productivity in tropical monsoon climates by mitigating season-specific environmental stresses [25,33].

4. Discussion

4.1. Microclimate Moderation and Its Physiological Implications

Our study confirms that the APV system creates a distinct microclimate characterized by reduced solar radiation, lower soil temperatures, and higher soil moisture, consistent with findings from both temperate and arid environments [25,35]. However, the physiological implications of these changes in a tropical monsoon climate differ significantly from those in high-latitude regions.

In temperate zones, light reduction by APV often limits photosynthesis and yield because solar radiation is a primary limiting factor [36]. In contrast, our results in Bogor suggest that the about 35% shading provided by the APV structure acted as a protective buffer rather than a limiting factor. Notably, while the maximum air temperature was significantly higher under the APV structure due to localized heat accumulation—likely caused by the resistance of the PV array to airflow [28,29]—this did not translate into yield penalties. Instead, the "cooling effect" was primarily manifested in the soil thermal environment. The significantly lower soil temperatures under APV ($p < 0.001$) likely protected the root system from thermal stress, preserving root functionality and water uptake capacity during the hottest periods of the day.

During the dry season, the "water-saving effect" of APV—evidenced by significantly higher soil moisture (Table 1)—became a critical driver. This aligns with Barron-Gafford et al. [35], who demonstrated that APV shading reduces evapotranspiration demand, thereby decoupling crop production from immediate precipitation deficits. This moisture conservation mechanism explains why the APV plot maintained high vegetative growth and yield even during the water-limited dry season.

4.2. Phenological Stability and Vegetative Plasticity

A major concern in APV cultivation is that shading may delay flowering or induce excessive stem elongation (Shade Avoidance Syndrome, SAS), potentially leading to lodging and yield loss [37]. However, our data showed no significant delay in phenological development (R1–R5) in either season (Figure 3). This supports the photothermal theory of soybean development, which posits that flowering is primarily regulated by photoperiod and temperature accumulation rather than irradiance intensity, provided light levels remain above the compensation point [19,30].

Interestingly, while APV plants exhibited greater height and leaf area in the vegetative stages, this vegetative plasticity did not result in negative agronomic traits. Instead, the significantly higher aboveground biomass ($p = 0.001$) and maintained node number in the wet season (Figure 5) suggest that the shade level (about 35%) was within the acclimation capacity of the 'Detap-1' cultivar. This finding contrasts with studies using denser shade (>50%), where significant reductions in node number and biomass have been reported [38]. It suggests that the specific APV design used in this study (sparse array, 3.1 m height) pro-

vides a balanced light environment that promotes vegetative vigor without compromising structural integrity.

4.3. Yield Formation Mechanism: Radiation Use Efficiency vs. Stress Mitigation

One of the most notable findings of this study is the significant yield advantage of APV observed in the wet season (+106%) and the moderate increase in the dry season (+17%). This result differs from the general trend observed in global APV meta-analyses, which often report yield penalties for major grain crops due to light limitation [36,39]. The mechanism behind this "tropical APV advantage" can be explained by the alleviation of environmental extremes.

Recent APV studies have emphasized that APV systems do not simply reduce total light availability but fundamentally modify the radiation regime at canopy level by attenuating excessive direct irradiance and increasing the proportion of diffuse radiation [40,41]. Such radiation modulation can enhance radiation use efficiency and mitigate photo-inhibition under high-radiation environments, particularly in warm climates.

In the wet season, the massive increase in number of pods per plant (72.2 vs. 43.9) under APV indicates that shading reduced reproductive abortion. Previous studies have established that heat and high-radiation stress during flowering (R1–R3) can significantly increase flower and pod shedding [32]. By lowering the thermal load, the APV system likely allowed a higher proportion of flowers to set pods. This interpretation is consistent with findings from grape-based APV systems, where moderated radiation reduced canopy stress and sustained physiological activity despite partial shading [41]. Furthermore, the significant increase in aboveground biomass implies that the open-field plants may have suffered from photoinhibition or saturation under intense tropical sunlight, whereas APV plants maintained efficient photosynthesis [25,33].

In the dry season, the higher HI under APV (36.2% vs. 30.3%) points to improved assimilate partitioning efficiency. Reference [34] noted that under drought stress, soybean plants prioritize survival over seed filling, typically reducing HI. The fact that APV plants maintained a higher HI suggests they experienced less physiological water stress, allowing sustained photosynthate translocation to seeds [27]. In this context, the reduced radiative and thermal load under APV likely contributed to maintaining photosynthetic function and carbon allocation efficiency under water-limited conditions, reinforcing the role of APV as a stress-buffering rather than light-limiting system. Thus, in tropical climates, the "stress-buffering" benefit of APV appears to outweigh the "light-limiting" cost, turning potential yield losses into significant gains.

4.4. Implications for Tropical Agrivoltaics

Our findings provide empirical evidence that APV is a highly viable strategy for sustainable intensification in tropical monsoon regions. Unlike in Europe or North America, where maximizing light transmission is the primary design constraint, tropical APV systems may benefit from shading levels that actively mitigate heat and drought stress. This "dual-benefit" creates a strong case for integrating energy generation with food production in Indonesia, contributing to the national renewable energy targets without compromising—and potentially enhancing—food security. Future research should focus on long-term soil health dynamics and the testing of diverse soybean genotypes to identify cultivars specifically adapted to the fluctuating light environments of APV systems.

In addition, this study focused on biophysical responses (microclimate and soybean performance) and did not quantify the structural resilience of the APV infrastructure or the techno-economic implications of below-PV cropping (e.g., wind-load design margins, CAPEX/OPEX, and machinery-related adaptation costs). Future work should integrate

structural engineering assessments and comprehensive cost–benefit analyses to evaluate climate-resilient APV designs and adoption feasibility in tropical cropping systems. Therefore, future research should aim to extend these findings through multi-site, multi-year trials employing randomized complete block design (RCBD) across diverse agro-ecological zones. Such expanded studies would allow for a comprehensive assess (Dment of the interactions between APV shading, soil types, and regional microclimates, ultimately supporting the development of standardized guidelines for scaling up APV systems in Indonesia and the broader tropical region.

4.5. Engineering and Techno-Economic Considerations for Climate-Resilient Tropical Agrivoltaics

While this study primarily quantified microclimate modification and soybean responses under an overhead APV structure, successful scaling of tropical agrivoltaics as a climate-adaptation option also requires engineering robustness and operational feasibility. Agrivoltaics can increase agricultural resilience by buffering crops against severe weather and climate stressors, yet the PV infrastructure itself must remain reliable under increasing climate hazards and within real on-farm constraints [42]. In particular, (i) wind/extreme weather risks for elevated structures, (ii) compatibility with farm machinery and field operations, and (iii) the cost premium and additional adaptation-related expenditures should be explicitly acknowledged when positioning tropical APV as a climate-resilient land-use strategy.

4.5.1. Wind/Extreme Weather Risk & Infrastructure Resilience

A climate-resilient APV concept should treat the PV structure not only as a shade provider but also as critical infrastructure exposed to extreme events. The IPCC Sixth Assessment Report indicates with high confidence that the proportion of intense tropical cyclones and peak wind speeds of the most intense tropical cyclones will increase on the global scale with increasing global warming, while evidence for changes in severe convective-storm characteristics such as severe winds remains of low confidence beyond increased precipitation rates [43]. Even when a specific inland site is not located in a primary tropical-cyclone belt, national or regional agrivoltaic deployment in tropical countries often includes coastal and archipelagic locations where extreme winds, gust fronts, and convective storm hazards can be relevant; therefore, robust wind design and operational risk management should be addressed as part of climate-resilient APV planning.

Elevated APV configurations are especially sensitive to wind loading. Design guidance for agrivoltaics notes that, as solar panels are installed higher off the ground, wind loading increasingly influences structural design, and rain/runoff effects can also affect land-management practices near panel edges [44]. Thus, clearance height and structural geometry should be determined by agricultural needs (e.g., machinery passage, crop type) while avoiding unnecessary elevation that increases wind exposure. Lessons from post-storm PV assessments further emphasize that survivability depends strongly on robust module attachments, system geometry, and sturdy racking rather than relying solely on module pressure-load ratings [45]. For elevated/canopy-like PV structures, excessive height can substantially increase wind loads; post-typhoon observations highlight that canopy systems built significantly higher than necessary were more susceptible to higher wind loads, and such structures should be built only as high as needed for their intended clearance [45]. These insights are directly relevant to overhead agrivoltaics because the "below-PV cropping" configuration inherently requires elevated mounting systems.

In addition to structural design, climate resilience is also an operation-and-maintenance (O&M) issue. APV systems may face increased soiling and a higher risk of damage or corrosivity of PV components due to farming activities and agrochemical applications,

which can influence both reliability and lifetime costs [42]. Accordingly, climate-resilient tropical agrivoltaics should incorporate (i) region-specific hazard assessment and structural engineering consistent with applicable wind codes/standards, (ii) strengthened attachment and racking strategies suitable for elevated systems, and (iii) O&M protocols for inspection and rapid repair after extreme events to minimize downtime and safeguard long-term performance.

4.5.2. Machinery Compatibility and Operational Adaptations

Machinery compatibility is a decisive, often under-discussed constraint for overhead agrivoltaics. APV design guidance emphasizes that PV layout and infrastructure may need to be updated for safe agricultural operations, including panel height and spacing, cabling/wire depth, irrigation placement, equipment placement, and perimeter setbacks [44]. Practical experience-based guidance also stresses that the APV mounting system should be aligned with the direction of tilling and that distances between supports must match the widths and heights of the machines used; impact protection on pillars can reduce damage risk during operations, and maneuvering between pillars requires an adaptation period for operators [46].

Clearance height is the central design variable for below-PV cropping. A guideline example indicates that a system geometry of roughly 3.5 m × 4.2 m spacing with a clearance height of 3.2 m can enable the use of standard agricultural machinery while keeping cabling within the roof structure to reduce interference during field work [46]. For stilted, overhead systems in arable farming, the clearance height is described as typically at least 5 m, with additional consideration needed for working width and headland space for machinery turning [46]. Consistently, a techno-economic case study of an APV demonstration system reported a clearance height of 5 m specifically to avoid hindering agricultural machinery—particularly combine harvesting—highlighting that high-clearance designs are often chosen to minimize operational disruption in mechanized systems [47].

Where local farming relies on smaller machinery or partially manual operations, alternative operational strategies may allow lower clearance heights and closer post spacing, potentially improving feasibility. In that regard, the agrivoltaics guideline notes that clearance height and post spacing strongly affect mounting-system cost and that using smaller farming machinery or performing more operations manually can improve cost-effectiveness [46]. For tropical smallholder or mixed-mechanization contexts, climate-resilient APV deployment may therefore require (i) early-stage machinery surveys (dominant tractor size, sprayer/harvester dimensions, turning radius), (ii) explicit headland and trafficability planning, (iii) protective measures for posts and cabling, and (iv) operational protocols (e.g., designated driving lanes, GPS/precision guidance where applicable) to reduce collision risk and avoid soil compaction.

4.5.3. Cost Premium & Adaptation Cost Considerations

From a techno-economic perspective, overhead agrivoltaics generally involves a cost premium relative to conventional ground-mounted PV, primarily driven by modified mounting structures and added design/coordination requirements. A bottom-up cost benchmark of dual-use PV reported an installed cost premium of approximately 0.07–0.80 USD/WDC over conventional ground-mounted PV, with the highest premiums observed for PV + crop configurations due to modified PV support structures; it also noted that site investigation and design costs tend to be higher because dual-use projects require additional planning and coordination with stakeholders such as farmers [48]. These findings align with broader agrivoltaic guidance describing that acquisition costs are generally higher than conventional ground-mounted PV—particularly for stilted, overhead systems—

because of higher, more elaborate mounting systems and (in some designs) specialized PV modules [46]. Importantly, as row spacing increases, land area requirements rise and costs can increase relative to electricity yield, creating a structural trade-off between agricultural operability (space/trafficability/light distribution) and energy/land-use efficiency [46].

For "climate-resilient" tropical APV framing, the relevant economic question is not only the baseline APV premium but also the incremental costs of hardening systems for future climate hazards. Storm-resilience guidance for PV infrastructure indicates that selecting modules with the highest published design wind ratings can more than double module cost compared to cheaper alternatives (e.g., approximately 1 USD/W vs. 0.40 USD/W in one documented procurement context), and vibration-resistant hardware and additional labor can also add meaningful upfront premiums [49]. While these figures are context-dependent, they illustrate that resilience measures can shift CAPEX and should be explicitly included in economic reasoning when responding to reviewer concerns about adaptation costs. Conversely, such costs may be justified by reduced repair needs, lower maintenance burdens, and improved ability to deliver power after severe-weather events—benefits that can be socially and economically valuable during climate-driven disruptions [49].

A key implication for integrated PV + below-PV soybean systems is that techno-economic evaluation should account for both (i) energy revenue and system reliability and (ii) agricultural value and avoided losses under heat/drought extremes. The dual-use PV benchmark stresses that understanding capital costs is only a first step and that additional data—including crop yield changes, water-use efficiency impacts, and O&M costs—are needed to assess lifetime cost and revenue effects and to clarify the value proposition under different scenarios [48]. Therefore, future tropical APV work would benefit from integrated analyses (e.g., scenario-based LCOE/NPV coupled with yield-stability benefits and risk-reduction under extreme climate events), explicitly separating (a) the baseline APV structural premium for below-crop operation and (b) incremental "climate-hardening" measures (wind/ corrosion/flooding/O&M) to provide transparent and decision-relevant evidence for policy and deployment.

4.6. Limitations and Future Research

While this study provides critical empirical data on soybean production under agrivoltaics in a tropical monsoon climate, certain experimental constraints inherent to commercial-scale infrastructure research should be noted. First, this study employed a single-plot-per-treatment design at a single site due to the logistical challenges and spatial requirements of installing a full-scale APV array. Accordingly, statistical analyses utilized plant-level subsamples ($n > 100$) as observational units. This approach was effective in rigorously capturing the within-plot variability and characterizing the immediate physiological responses of the crop to the modified microclimate, providing a robust baseline for understanding APV-crop interactions.

Second, although the experiment encompassed distinct wet and dry seasons, the data represent a single-year cycle. Given the inter-annual variability of tropical weather patterns—particularly regarding rainfall distribution and El Niño-Southern Oscillation events—continuous monitoring is essential to confirm the long-term stability of the observed yield advantages.

In addition, the fixed APV structure used in this study did not include a rainwater collection or redistribution system. During the dry-season cultivation, when rainfall events were concentrated into a limited number of high-intensity events, localized lodging of soybean plants was observed beneath the panel edges due to concentrated water discharge. To mitigate this effect, additional plant supports were installed during the cultivation period, which reduced further lodging and allowed normal crop development to con-

tinue. Although this management intervention limited its influence on final yield, the observation highlights a practical limitation of fixed agrivoltaic systems under tropical rainfall conditions and underscores the need for site-specific drainage design and structural mitigation strategies.

Therefore, future research should aim to extend these findings through multi-site, multi-year trials employing RCBD across diverse agro-ecological zones. Such expanded studies would allow for a comprehensive assessment of the interactions between APV shading, soil types, and regional microclimates, ultimately supporting the development of standardized guidelines for scaling up agrivoltaic systems in Indonesia and the broader tropical region.

5. Conclusions

This study quantitatively evaluated the effects of an APV system on the microclimate, growth, and yield of soybean (Glycine max) across wet and dry seasons in the tropical monsoon climate of Bogor, Indonesia. The results demonstrated that the about 35% reduction in solar radiation by the APV structure did not hinder crop growth but rather induced positive microclimatic modifications by mitigating excessive radiative loads and moderating soil temperatures, while effectively conserving soil moisture.

These environmental benefits translated into distinct yield advantages in both seasons. In the wet season, the APV system shielded the crop from intense solar radiation and soil heating, maximizing pod formation and resulting in a remarkable 106% yield increase compared to the open field. In the dry season, the superior moisture conservation under APV alleviated physiological water stress and improved assimilate partitioning (HI), leading to a 17% yield gain. Furthermore, phenological development (R1–R5) was not delayed under APV conditions, and vegetative growth was maintained or enhanced, confirming that the reduced light levels remained sufficient for soybean physiological processes.

In conclusion, this study validates that in tropical climates, APV systems serve not merely as a dual land-use strategy but as an effective climate adaptation technology that protects crops from intensifying environmental stresses. These findings suggest that APV offers a sustainable solution for equatorial nations like Indonesia to achieve renewable energy targets without compromising—and potentially enhancing—food security. Future research should address the economic feasibility of such systems, alongside long-term assessments of soil fertility dynamics and genotype-specific adaptability under varying meteorological conditions.

Author Contributions: Conceptualization, S.Y., S.H. and J.-Y.L.; Data curation, S.Y., M.K. and S.H.; Methodology, S.Y., M.K., S.H. and J.-Y.L.; Project administration, J.-Y.L.; Supervision, J.-Y.L.; Visualization, S.Y. and M.K.; Writing—original draft, S.Y. and M.K.; Writing—review and editing, S.Y., M.K., S.Y. and M.K. contributed equally to this work. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Korea East-West Power Co., Ltd. (EWP) under the project "Indonesia 50 kWp Agrivoltaics–E-mobility system Integration". The APC was funded by the same source.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: During the preparation of this manuscript, the authors used generative AI tools for language editing and improving sentence clarity. The authors have reviewed and edited the content and take full responsibility for the final version of the manuscript.

Conflicts of Interest: Authors MinKyoung Kim and SeungYeun Han were employed by ENVELOPS Co., Ltd. This study received funding from Korea East-West Power Co., Ltd. (EWP) under the project

"Indonesia 50 kWp Agrivoltaics–E-mobility Integrated Demonstration Technology Development." The funder had no role in the study design; data collection, analysis, or interpretation; manuscript preparation; or the decision to publish. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

APV	Agrivoltaic/Agrivoltaics
CEC	Cation Exchange Capacity
DAS	Days After Sowing
HI	Harvest Index
LER	Land Equivalent Ratio
PV	Photovoltaic
RCBD	Randomized complete block design
R1	Beginning bloom (reproductive stage)
R3	Beginning pod (reproductive stage)
R5	Beginning seed (reproductive stage)
SD	Standard Deviation
WAS	Weeks After Sowing

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