AIMS Energy, 13(5): 1076–1103.
DOI: 10.3934/energy.2025040
Received: 11 May 2025
Revised: 26 August 2025
Accepted: 01 September 2025
Published: 11 September 2025

https://www.aimspress.com/journal/energy

Review

Agrivoltaics systems in Indonesia: Opportunities, challenges, and lessons from other countries

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Abstract: Indonesia, with its large population and rapid economic growth, is facing equally important issues of food and energy security. While Indonesia is also committed to achieving net zero emissions (NZE) by 2060 or sooner, it remains heavily dependent on fossil energy at 87%. Yet Indonesia has enormous renewable energy potential, with solar energy having the greatest potential with an estimated 3,294 gigawatt-peak (GWp). This research reviews and summarizes the development of agrivoltaics research in Indonesia and compares it with the development of agrivoltaics research globally to see the opportunities, challenges, and lessons from countries that have developed agrivoltaics in an advanced and extensive manner. The results indicate that the number of agrivoltaics research studies in Indonesia remains very limited, highlighting the need to encourage further research with a focus on crop compatibility and strategic crops. Studies have shown that potato, tomato, and garlic, which are classified as strategic crops in Indonesia, are well-suited for cultivation under agrivoltaics systems. This compatibility enables the simultaneous optimization of the country's substantial solar energy potential alongside sustainable food production. Agrivoltaics minimizes massive land requirements to avoid competition with agricultural land, increase land use efficiency, and reduce the potential for deforestation. However, agrivoltaics has the potential to reduce agricultural productivity and it is costly, requiring proper planning and selection of appropriate crops, as well as

policy and financial support. In addition, agrivoltaics also has the potential to increase the efficiency of solar panels due to the placement of plants, thus reducing the temperature around solar panels.

Keywords: agrivoltaics; solar energy; net zero emission; land use efficiency; renewable energy

1. Introduction

As one of the world's most populous countries with a rapidly developing economy, Indonesia faces the dual challenge of ensuring food and energy security, both of which require vast amounts of land. Clearing land to develop and increase agricultural and energy production will also trigger deforestation, as Indonesia is one of the world's largest carbon sinks [1–3]. In fact, it will worsen the climate change conditions that affect agricultural productivity and even cause crop failure due to drought or flooding. A sustainable and environmentally friendly solution is needed to improve productivity while minimizing the negative effects on the environment [4,5]. Renewable energy development is also necessary, as Indonesia has committed to achieve net zero emissions (NZE) by 2060 or sooner according to the Updated Nationally Determined Contribution document, which requires a significant transformation in the energy mix through green technologies [6–8].

At present, Indonesia still relies on fossil fuels to fulfil its energy demand for electricity generation. Coal, natural gas, and oil have the highest portion of around 87% according to the report in 2019 [9]. Renewable energy utilization has only a small portion of around 13% of the total national energy generation of Indonesia, even though Indonesia is in an area that has a huge potential and vast resources for solar, wind, geothermal and hydropower energy [10]. The solar energy has the biggest potential amongst the renewable energy resources [11,12].

The geographic position of Indonesia brings vast solar energy power, with the average daily solar irradiation being 4.8 kWh/m^2 and approximately 1,752 kWh/m^2/year [1,13]. Solar photovoltaic (PV) utilization has a big prospect to improve renewable energy power generation, despite the fact that a large-scale construction of solar power plants requires an enormous amount of land area (or water) that would potentially triggers a shift in the function of agricultural land that also is very important for food security and other national interests of Indonesia, where the agriculture land availability has already competed with housing and industrial land area demand [1,14]. It also can trigger deforestation that worsens climate change, so a better comprehensive solution is needed, such as constructing a solar power plant above an agricultural area, a lake, or a rooftop area to maximize land utilization [15–17].

The agrivoltaics system offers an innovative solution to solve the dilemma of land availability and usage by integrating agriculture and solar energy generation on the same land. The integration of these two activities not only optimizes land utilization but also gives potential benefits for solar PV and the agricultural environment [18–20]. While agrivoltaics has been widely praised for its potential benefits, such as reducing solar PV temperatures to improve efficiency and lowering crop water requirements by mitigating excessive sunlight exposure, these positive impacts are often context-dependent. For instance, reference [21] highlights that such advantages are primarily observed in arid regions, where shading can significantly reduce evapotranspiration and improve crop productivity. Similarly, reference [22] reports favorable outcomes in extremely arid conditions. However, reference [23] notes that while several crops showed no negative effects under agrivoltaics systems, rice, a staple crop in Indonesia, was adversely affected due to its sensitivity to reduced light. These findings suggest that while agrivoltaics holds promise, its implementation in tropical regions like Indonesia requires a nuanced approach that considers crop-specific responses and local climatic conditions to ensure sustainable and realistic outcomes. To get a positive impact on both sides, the crops should be suitable for the effect of shading from the solar PV installation and the optimum solar PV configuration that can optimize energy production [24,25]. Several global research found the effect of shading on crop yield. Growing crops with agrivoltaics systems can lead to either increases or decreases in yield, as some crops experience around a one-third reduction in solar radiation. However, by integrating energy and crop production, agrivoltaics systems can enhance land productivity by up to 70% [21].

Globally, there are several terms used to mention the combination of solar PV and agricultural land to improve land use efficiency and provide additional benefits between the two systems, namely agrophotovoltaics in Germany, solar sharing in India, and PV agriculture in China [26]. According to the available references, the agrivoltaics concept was proposed for the first time in 1982 by Goetzberger and Zastrow, where they placed solar power plants in agricultural land by modifying the placement 2 meters above the land to not interfere with the agricultural activity, and widening the gap between each panel so as not to overshade the crops [27,28]. Even though there are some challenges, such as the high initial investment and the potential productivity reduction, it will improve the land usage efficiency by producing energy and crops simultaneously.

This research is conducted to study the application and development of agrivoltaics research in Indonesia from 2014 to 2025, then compare it with the application in developed countries that have developed agrivoltaics that reach an industrial scale and identify the opportunities and challenges of applying agrivoltaics in Indonesia by studying the best practices around the globe and take lessons from international experiences. This study tries to give insight into an effective method to integrate the agrivoltaics system in Indonesia that is able to support the energy transition as well as ensure sustainable agricultural productivity.

2. Materials and methods

In conducting the process of writing this research paper, as shown in Figure 1, it started with collecting previous research on Google Scholar and ScienceDirect using the keywords Agrivoltaics in Indonesia, Agrophotovoltaics in Indonesia, PV Agriculture in Indonesia, and Solar Sharing in Indonesia in the period from 2014 to January 2025. Agrivoltaics, Agrophotovoltaics, PV Agriculture, and Solar Sharing are some terms that refer to integration of PV panels and crops [21,26]. This review paper was conducted following the structured layer approach for systematic reviews [29,30].

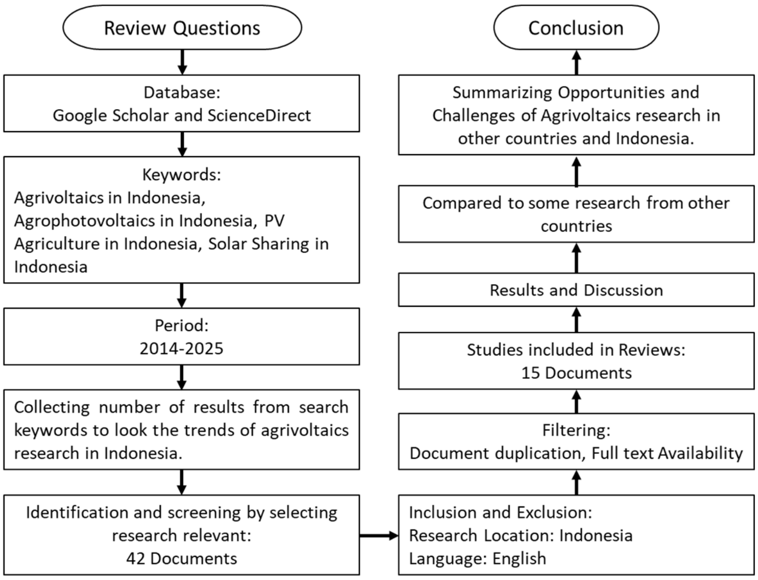

Figure 1. Flow chart of the review study.

Next, because the novelty of research applies globally, it is necessary to compare the findings that have been obtained and the level of research development on a global scale [31,32]. Furthermore, these results were summarized to see the technical matters that need to be considered, such as determining the crops and the configuration of the solar panels [17,25,33]. It can be used as a reference to be adopted according to existing conditions in Indonesia such as crops, agricultural machinery, and environmental conditions.

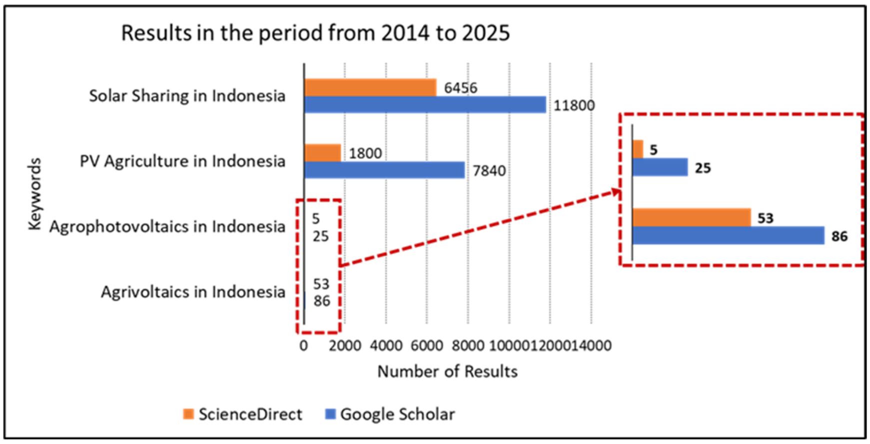

Figure 2. Results in Google Scholar and ScienceDirect in the period from 2014 to 2025.

The search results in Google Scholar and ScienceDirect, as shown in Figure 2, shows that Solar Sharing in Indonesia and PV Agriculture in Indonesia are the highest, with the number in Google Scholar being higher than in ScienceDirect. The number of searches for PV Agriculture in Indonesia on ScienceDirect was only a quarter of Google Scholar, and Solar Sharing in Indonesia on ScienceDirect is about 50% less. On the other hand, Agrophotovoltaics in Indonesia and Agrivoltaics in Indonesia showed few results in searches on Google Scholar and Science Direct. Figure 3 shows the results of keyword searches by year from 2014 to 2025 on Google Scholar and ScienceDirect.

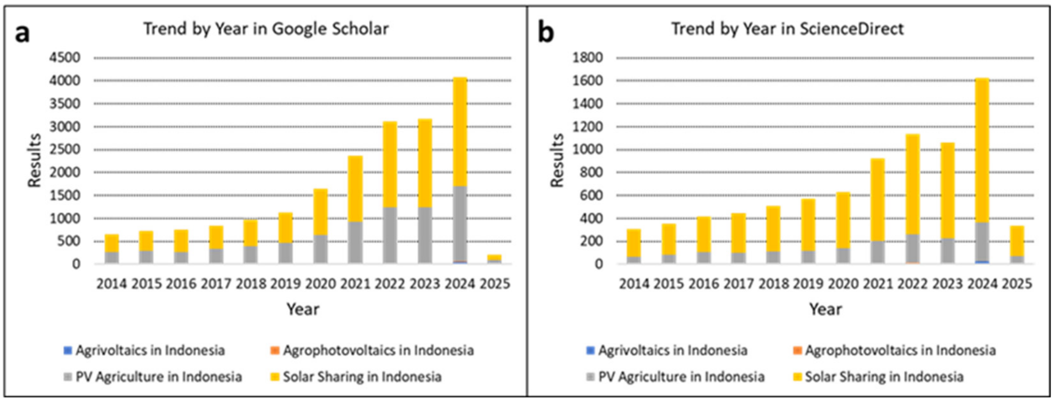

Figure 3. Trend of results by year in (a) Google Scholar and (b) ScienceDirect.

The trend of search results based on year-to-year tends always to increase, even though the number of ScienceDirect searches in 2023 decreased slightly and the results in 2025 is the number in January 2025. Research on the integration of solar power generation and agriculture are increasingly needed because of the large land requirements due to the availability of land getting smaller and more expensive. In addition, the acquisition of new land for agriculture or solar power generation will encourage deforestation [1,34].

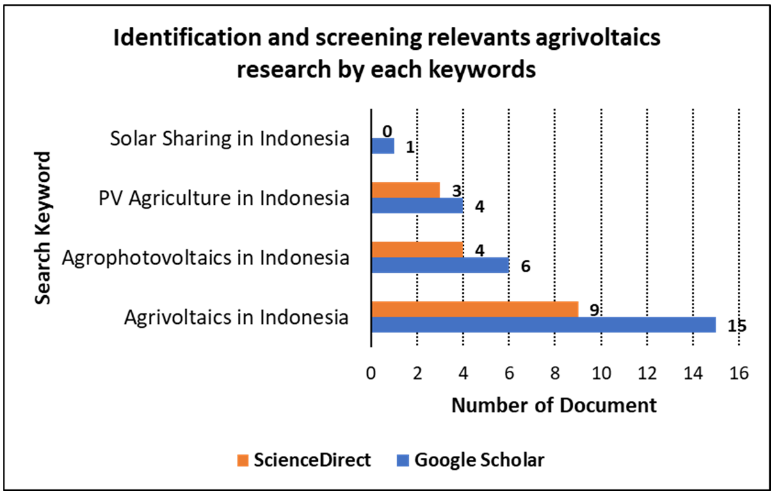

Figure 4. Identification and screening of relevant agrivoltaics research by each keyword.

The search results shown in Figure 4 indicate that the term Agrivoltaics is the most relevant and widely used. These results contrast with the search results for PV in Agriculture in Indonesia and Solar Sharing in Indonesia which yield many results but do not refer to the agrivoltaics concept as intended. The total identification and screening resulted in 42 research papers that addressed or were related to agrivoltaics research.

Eligible documents were selected by applying inclusion and exclusion criteria based on location in Indonesia and English language documents. To avoid duplication and ensure full-text availability, a filtering process was conducted. As a result, 15 research papers were selected for this study. The papers which were obtained for this review were divided into two categories: Research articles and review articles. Research articles were studies that conduct original experiments or analysis, while review articles synthesize previous research. From these 15 selected papers, the authors' affiliations, research locations, and key findings were then identified.

3. Results and discussion

3.1. The state of agrivoltaics research in Indonesia and its global context

The 15 research papers on agrivoltaics in Indonesia consist of 13 research articles and 2 review articles (Figure 5a). Figure 5b shows the number of papers published from 2021 to 2025. The highest numbers of papers were published in 2023 and 2024, with six papers each, followed by one paper in each of the years 2021, 2022, and 2025.

According to the affiliations, there are 28 research institutions or universities consisting of 25 domestic institutions and 3 foreign institutions. As shown in Figure 6, Politeknik Negeri Sriwijaya is the affiliation that has the most occurrences (six times), followed by the National Research and Innovation Agency (BRIN) (four times), then the University of North Sumatra, Bandung Institute of Technology, Gadjah Mada University, and Sriwijaya University (three times each). Besides that, there are still 19 other institutions that appear one time each. There are also four overseas institutions Falck Renewable North America, National Renewable Energy Laboratory, and Temple University, one time each.

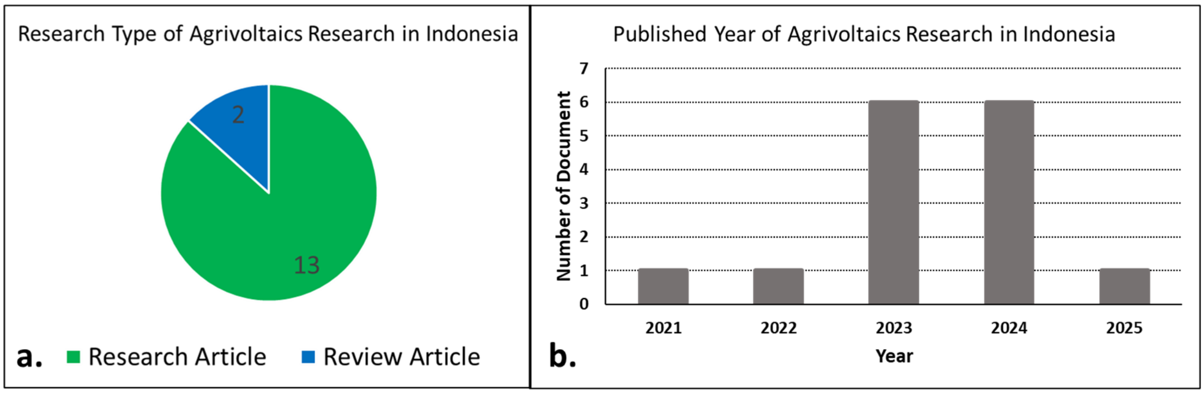

Figure 5. Research type (a) and publication year (b) of agrivoltaics research in Indonesia.

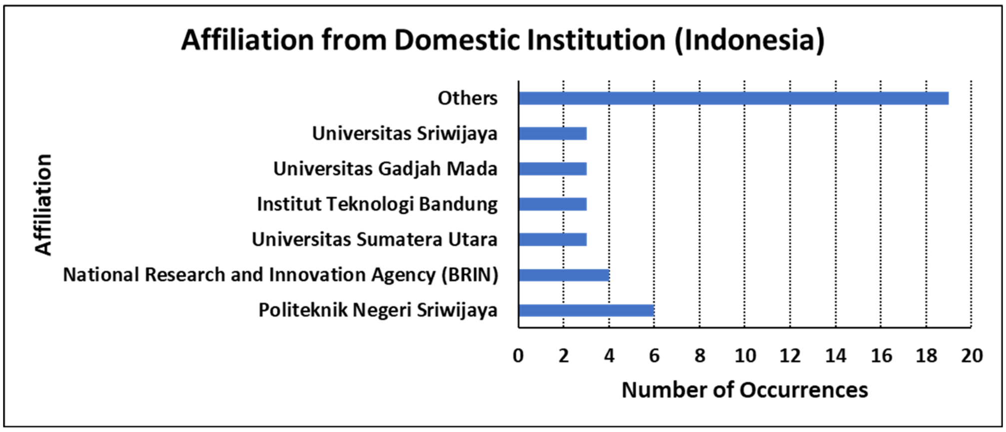

Figure 6. Affiliation of agrivoltaics research in Indonesia.

The use of PV panel technology is important for sustainable agriculture, reducing environmental impacts, and increasing energy efficiency to support greenhouse operations, especially in remote areas [35–38]. There are some articles that discuss specific crops such as patchouli, peanuts, tomatoes, and green beans, which are indicated to be tolerant to shading, and some articles use software to see the potential of agrivoltaics [5,39,40].

Furthermore, all the papers that conducted experimental studies used horticulture vegetable crops such as eggplant, spinach, pakchoi, bok choi, chaisim, and kailan [41–43]. Some focus on other horticulture crops such as mustard, pepper plants, and chili [44–47]. But some do not focus on crops but use energy from solar panels for smart irrigation and provide electricity for agricultural activities to reduce dependence on fossil energy [48].

An analysis of the available data suggests that research on agrivoltaics in Indonesia remains limited, with a relatively small number of studies, even without filtering for globally indexed publications such as Scopus. To provide data-driven evidence, a bibliometric analysis on co-authorship by countries was conducted using the Scopus database with the keyword Agrivoltaics and visualized through VOS viewer software. This aimed to know the positions of Indonesia in agrivoltaics research. As illustrated in Figure 7a, the country's co-authorship analysis reveals that Indonesia is not represented, indicating the country's lack of agrivoltaics research contributions. Furthermore, Figure 7b presents the top 20 countries according to the number of published documents and citations in agrivoltaics research, with the United States, Germany, China, Spain, and Italy emerging as the top five contributors in terms of research output.

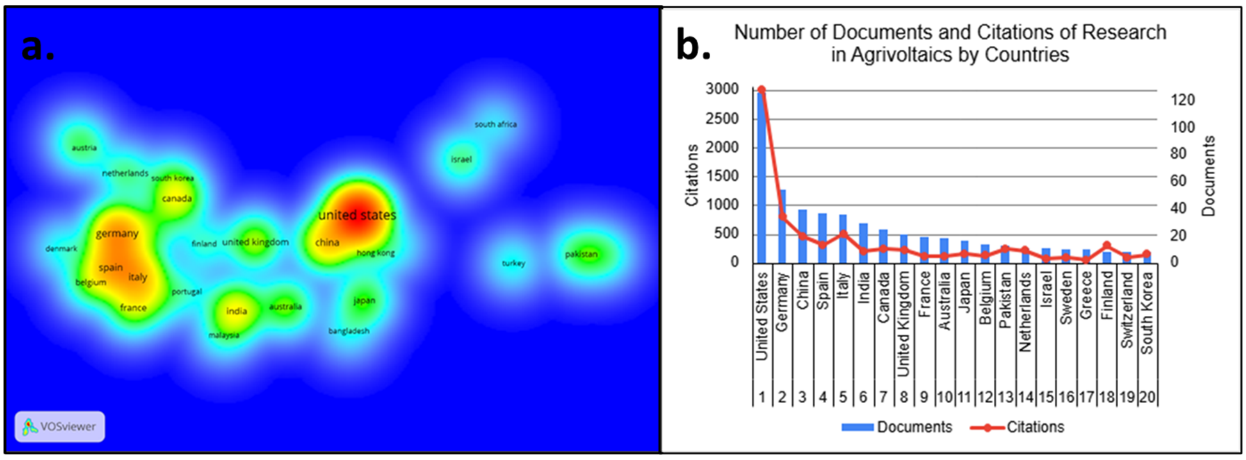

Figure 7. Global agrivoltaics research landscape: Co-authorship (a) and document contribution (b) by country.

3.2. Impact of agrivoltaics systems on solar panels and cropland

Table 1 provides information on the location of the research and information on the crops used as the focus of the research. The types of plants used, as explained in the previous section, are horticultural types of crops that have high added value so that they can provide good benefits for farmers. In addition, many horticultural crops also show tolerance to shading effects, and artificial shading is usually used to make them suitable for planting under agrivoltaics systems [49].

The location where agrivoltaics research was carried out is spread across western and central Indonesia, with most of it carried out in Sumatra and Java, which is relevant, because this is the most populous region with decreasing land availability due to competition with land for housing and industry [50,51]. Moreover, many forest areas need to be preserved, so wise land use is needed rather than deforestation, which destroys nature for increased agricultural or energy production [52,53].

According to the list of agrivoltaics research in Indonesia, studies have focused on the effect of solar panels on crop and there are no studies examining the impact of crops on PV panels. Although referred to as an agrivoltaics system, some studies, as shown in Figure 9, do not directly integrate PV panels on agricultural land [42,44,46,48]. Consequently, these studies do not affect microclimatic conditions, which can either enhance or limit plant growth, depending on the crop species and local environmental factors [21,22].

Several studies have demonstrated that shading from PV panels can benefit certain crops with little to no effect on others. In Baron Technopark, Yogyakarta, Ahmad et al. [41] expected no yield reductions with eggplant planted under shading. While Setyorini et al. [45] conducted research at the same location and showed that eggplant was affected by shading, while mustard greens showed no significant difference in growth compared with those grown in open fields. Research in South Sumatra revealed that chili and bell pepper yields increased under agrivoltaics conditions, particularly when supported by optimized irrigation and monitoring systems [44,46].

In East Java, although it is not an agrivoltaics system, the use of solar panels to supply electricity for vertical farming and LED lighting has increased vegetable production and reduced energy costs [42]. Other findings highlight that some crops demonstrate high adaptability to shading. For instance, in West Java, patchouli plants experienced minimal yield reduction under PV panels [5]. Meanwhile, research in

Bandung indicated that bok choy cultivated under semi-transparent PV (STPV) panels exhibited similar growth rates to those in full sunlight [43]. In Medan, improved agricultural management within an integrated Internet of Things (IoT) system has shown potential for monitoring chili production [47]. Furthermore, research in Central Java found that peanuts, tomatoes, and green beans had the potential to tolerate partial shading, making them well-suited for agrivoltaics applications [39].

Table 1. Effect on crop yield in some research locations in Indonesia.

Location	Crops	Effect on Crop Yield	Ref.
Yogyakarta	Eggplant	Potentially no reduction in yield.	[41]
Yogyakarta	Mustard, Eggplant	Mustard is not too impacted. Reduced growth and yield of eggplants.	[45]
South Sumatra	Pepper plants	Improved growth and yield due to optimized irrigation and monitoring.	[44]
South Sumatra	Chili	No mentioned effect on crop yield. Focus on convolution neural network (CNNs) to predict harvest yield.	[46]
West Java	Patchouli	Potentially no great reduction in yield.	[5]
Bandung	Bok choy	The mean crop yields are 1.4–1.8% greater.	[43]
Medan	Chili	No mentioned effect on crop yield. Focus on the Internet of Things system in farming area.	[47]
Central Java	Peanuts, tomatoes, green beans	Potentially no reduction in yield.	[39]

Beyond its effect on crops, agrivoltaics farming also can produce electricity for supplying energy in agricultural activities. In South Sumatra, solar energy generated from PV panels supports agricultural operations, including greenhouse management, with an estimated annual energy output of 1,744.67 kWh [46]. In Bandung, STPV panels were found to distribute light more evenly, reducing the uneven shading effects commonly associated with traditional PV panels. Semi-transparent PV modules installed at approximately 3 m height with a 20° tilt facing north achieved high light uniformity ($U_0 > 0.88$ in simulation and $\approx$ 0.95 in the field) while maintaining the growth performance of bok choy (*Brassica rapa* var. *chinensis*) similar to unshaded conditions. The study indicated that a light transmission level of around 40–50% provided a favorable balance, reducing heat stress and water loss in plants while ensuring sufficient solar irradiance for electricity generation. This suggests that in the Indonesian context, crop types with moderate shade tolerance (e.g., leafy vegetables, chili peppers) could be paired with elevated semi-transparent PV modules using similar configurations to optimize both yield and energy production [43]. Overall, these studies illustrate the potential of agrivoltaics systems to enhance both agricultural productivity and renewable energy generation. By carefully selecting crop types and optimizing PV panel configurations, agrivoltaics farming can be a sustainable solution for improving food security and energy efficiency in Indonesia.

Table 2 summarizes the effects of agrivoltaics systems on crop yields and solar panels, along with research locations in several countries. The impact on crop yield is expressed as the percentage change relative to open-field control yields, allowing for direct comparison across studies. For descriptive purposes, yield changes can be interpreted as negative (substantial reduction, e.g., ≤–20%), moderate (small reduction to no change, between 0% and –20%), or positive (increase above control yield). For example, some studies on potato and spinach report yield improvements, while results for rice and lettuce vary from moderate reductions to substantial decreases, depending on the shading level. Crops such as soybean and maize/corn also show mixed outcomes, with negative impacts observed under higher shading conditions. This variability underscores the importance of considering both the crop type and system's parameters, such as shading rate, PV placement, and ground coverage ratio, when assessing agrivoltaics performance.

Some crops that show positive to moderate effects are potato and tomato, where potato plants adapt well to low solar radiation conditions and show good growth under PV modules [54–56]. Tomatoes showed double the production under solar panels, although the layout and crop ratio to solar panels need to be considered [22,55,57]. But there are also crops that show moderate to negative results, such as soybeans where there is a decrease of less than 20% at a 20% shading rate and more than 20% at a 30% shading rate, and yield can even decrease to 61% under a 40% shading rate [34,57,58]. Corn/maize crops also show a dominant negative effect under agrivoltaics systems and can decrease to 55% under balanced conditions between cropland and solar panels and even to 9% when maximizing electricity production [34,55]. This is consistent with the study conducted by [59], which identified a general trend that an increase in the number of solar panels (ground coverage ratio/GCR) in agrivoltaics systems tends to reduce crop yields. The study demonstrated that as the GCR increases, the relative yield (RY) of crops significantly declines. For instance, at GCRs below 25%, most crop RYs remain above 80%, whereas at higher GCRs, the RY rapidly decreases. This suggests that a higher number of panels (higher GCR) leads to more shading, which, in turn, can reduce overall crop yields. However, in other studies, corn/maize shows that losses can be minimized by maintaining low shading and forage yield of corn, and there is no significant negative effect [18,23].

In addition, some crops showed moderate effects, such as rice crops, which decreased by 8.9% to 18.7% under the agrivoltaics system and even showed no significant decrease in the vertical agrivoltaics system [23,33]. Other studies showed almost the same production results compared with conventional cultivation and some showed a decrease but still below 20% at a 20% shading [4,58]. However, there are studies that show a decrease of up to 55% in half-density conditions and even a decrease to 9% when maximizing the layout of PV panels to maximize electricity production [34]. Other crops, such as garlic and onion, showed a decrease below 20% under PV panels, and grapes showed no significant decrease by maintaining a maximum shading of 30% [23,60]. Lettuce showed a moderate impact from shading, maintaining about 79% of the open field yield even under 50% shading conditions [19,61], indicating only a 21% yield reduction. This measurement was obtained under actual agrivoltaics field conditions, where PV panels reduced incident photosynthetically active radiation (PAR) while allowing partial light transmission. The observed yield reduction is primarily attributable to lower PAR beneath the panels. Lettuce, being shade-tolerant, can physiologically compensate for reduced light by expanding leaf area to increase light interception [19].

According to [59], crop yield response in agrivoltaics depends not only on shading intensity but also on microclimatic modifications, water availability, and the occurrence of extreme events. Moderate shading can reduce canopy and soil temperatures, lower evapotranspiration, and improve water-use efficiency, factors that may offset light reduction under water-limited conditions. Conversely, excessive shading from a high GCR can drop yields below economically viable levels; Dupraz suggests that keeping GCR below ~25% generally maintains yields above 80% of open-field conditions. Furthermore, shading can mitigate yield losses caused by frost, hail, sunburn, or heat stress, meaning that in certain climates, protective effects may outweigh reductions in PAR [59]. This process-level understanding indicates that for lettuce, a shade-tolerant crop, the balance between light reduction and microclimatic benefits is crucial. Optimizing panel density and configuration can enable sustained production while delivering additional environmental co-benefits.

Furthermore, some research does not discuss the effects on solar panels in agrivoltaics systems because it focuses more on the effects on crops [18,54,57]. Agrivoltaics systems could make a significant impact by generating electricity and contribute to increased renewable energy production [60]. However, research that discusses the effects of agrivoltaics systems on solar panels shows a positive impact by combining PV panels with crops because shading will reduce evapotranspiration and soil temperature, thus reducing the temperature in the agrivoltaics system's area [61,62]. The decrease in temperature in the agrivoltaics system's area will affect the decrease in solar panel temperature, increasing efficiency where the solar panel temperature is lower by about 8 °C [22]. However, the placement of PV panels in agricultural areas will have the potential for dust accumulation, which will reduce efficiency, so cleaning is necessary [19]. The cleaning of PV panels can be integrated with an irrigation system where the water used to clean the PV panels is channeled to water the plants to minimize water wastage [22].

Table 2 presents an overview of agrivoltaics research conducted globally, summarizing the measured effects on both crop yield and PV performance, along with the available design parameters such as shading rate, PV height, and system configuration. As shown in Figure 10, agrivoltaics trials have been implemented in diverse climatic and agricultural contexts across America, Europe, and Asia, including the USA, Germany, Spain, Italy, France, China, India, Japan, Pakistan, Bangladesh, and South Korea. These initiatives aim to enhance land use efficiency by simultaneously generating electrical energy and maintaining agricultural production. Several countries, such as China and Italy, have advanced to commercial-scale installations, with capacities reaching 3,230 kWp in Monticelli D'Ongina, Italy, and 30,000 kWp in Zhejiang, China [21].

This global progress provides valuable insights and benchmarks for Indonesia, where agrivoltaics research is still limited. While there are no data on the types of crops grown under agrivoltaics systems that can be directly compared between agrivoltaics research in Indonesia and globally, there are three studies combining plants and solar panels directly, as conducted by K. Ahmad et al. [41] and T. Setyorini et al. [45] in Baron Technopark, growing eggplant and mustard, and by S. Apriani et al. [43] in Bandung, growing bok choy, which is a type of cabbage. This research shows a positive effect on crops and potentially a positive impact on solar panels as well.

Table 2. The effect of agrivoltaics systems on several crops' yield and on solar panels in several countries (global).

Location	Crops	Effect on crop yield	Effect on solar panel	Ref.
Kyungpook National University Experimental Farm, South Korea	Rice	−8.9% to −18.7%	Shading rate: 30%; GCR: 27.3%; PV height of 3.3 m; Tilt angle: 35°	[23]
Gunwi, South Korea	Rice	−7.2% (max)	Vertical bifacial system optimized for energy capture; GCR: 28.8%; Vertical PV height: 2.957 m	[33]
Bosung and Naju, Chonnam Province, South Korea	Rice	−18.1% (20% shading). −27.1% (30% shading). −37.5% (40% shading)	PV panel height: 6 m; Tilt angle: 35°; Shading rate: 20%, 30%, 40%.	[58]
Kansas City, USA	Lettuce	−42% in FD (summer). −19% in HD (summer). −21% in FD (spring). ~0% in HD (spring).	PV Panel height:4 m; GCR: 23.8% (HD), 31.7% (FD)	[19]
Montpellier, France	Lettuce	−21% (30% shading), −42% (50% shading)	Lower panel temperature but no quantified PV gain; Shading rate: 30% (HD), 50% (FD); GCR: 22.8% (HD), 45.6% (FD); PV panel height: 4 m; Tilt angle: 25°	[61–63]
Biosphere 2, University of Arizona, Tucson, AZ, USA	Tomato	+100%	Panels ~8.9 ℃ cooler, improving efficiency and energy output; PV panel height: 3.3 m	[22]
Kyungpook National University Experimental Farm, South Korea	Corn/maize	~0% (forage yield)	Shading rate: 30%; GCR: 27.5%; PV panel height: 3.3 m; tilt angle: 35°	[23]
Bosung and Naju, Chonnam Province, South Korea	Soybean	−18.3% (20% shading). −28.3% (30% shading). −38.6% (40% shading)	PV Panel height: 6 m; tilt angle: 35°; shading rate: 20%, 30%, 40%.	[58]
Montpellier, France	Cucumber	Reduction in leaf number and dry matter accumulation (no % yield data)	Lower panel temperature but no quantified PV gain; Shading rate: 30% (HD), 50% (FD); GCR: 22.8% (HD), 45.6% (FD); PV panel height: 4 m; tilt angle: 25°	[62,63]

Continued on next page

Location	Crops	Effect on crop yield	Effect on solar panel	Ref.
Kyungpook National University Experimental Farm, South Korea	Garlic	−14.4%	Shading rate: 30%. PV height of 3.3 m; Shading rate: 30%.; GCR: 27.5%; tilt angle: 35°	[23]
Kyungpook National University Experimental Farm, South Korea	Onion	−18.7%	Shading rate: 30%; PV panel height: 3.3 m; Shading rate: 30%; GCR: 27.5%; Tilt angle: 35°	[23]
Cheongju, South Korea	Potato	~0%	Shading rate: 25−32%; PV panel height: 4−4.5 m;	[56]

Based on BPS-Statistics (*Badan Pusat Statistik*) Indonesia and Directorate General of Horticulture, Ministry of Agriculture (MoA) of the Republic of Indonesia, there are 18 strategic horticultural products in Indonesia. The products are shallot, garlic, big chili, cayenne pepper, potato, tomato, carrot, banana, durian, orange, mango, pineapple, mangosteen, ginger, turmeric, java turmeric, cut orchid, and chrysanthemum. It is an opportunity to develop research and apply agrivoltaics technology to increase solar power capacity in conjunction with strategic commodities in Indonesia. Studies on strategic crops like potato and tomato have shown positive outcomes in certain climates, such as the significant yield increase for tomato reported by Barron-Gafford et al. [22] in arid regions. Similarly, research in South Korea found that potatoes cultivated under an agrivoltaics system maintained growth and yield comparable with those grown in full sunlight, demonstrating their suitability for such systems [56]. However, it is important to note that these results are context-dependent, and further research is needed for Indonesia's specific environmental conditions. Success in agrivoltaics is not solely dependent on a positive effect on crop yield, as even a slight reduction may be offset by the additional income from electricity generation and an increase in overall land use efficiency [17,64]. Another strategic horticultural crop that needs further research is garlic, as consumption in Indonesia is very high, up to 552,480 tons in 2023 [65]. Moreover, garlic shows a moderate effect that can be optimized with the right combination with solar panels [23].

Additionally, research that addresses the impact on solar panels related to the effect of decreasing temperatures in agrivoltaics areas due to the effects of surrounding plants is minimal. A decrease in temperature can increase the efficiency of solar panels because every 1 ℃ increase in temperature above 25 ℃ will reduce the average efficiency by about 0.6%/℃ [22]. This can be an opportunity for further research that focuses on the effect on the efficiency of solar panels on agrivoltaics.

3.3. Agrivoltaics configuration

The agrivoltaics concept is usually known as placing solar panels on agricultural crops by modifying the height of the solar panels' poles so that agricultural activities using agricultural equipment can still run [4,5]. The placement of solar panels directly above agricultural crops, according to the general concept globally in Indonesia, was carried out at Baron Technopark as shown in Figure 8a,b using eggplant and mustard plants. The field experiment used seven solar panels with a capacity of 36 kilowatt-peak (kWp) with a fixed tilt angle, placing the plants under the panel and outside the panel to see the shading effect [41,45]. As shown in Figure 8c, the experiment was conducted in Bandung on bok choy plants using a STPV module at a height of 3 m, and the solar panels facing north with the optimum tilt angle obtained at 20º [43].

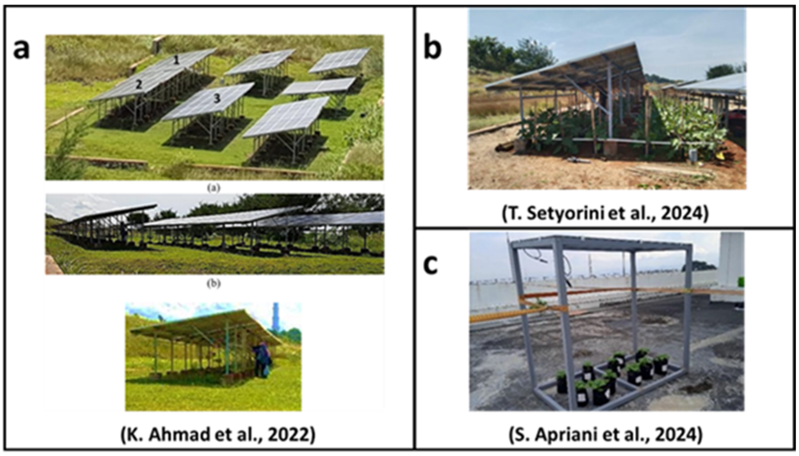

Figure 8. Agrivoltaics field experiment in Baron Technopark using eggplant and mustard [41,45] (a,b) and an agrivoltaics field experiment in Bandung using bok choy and STPV modules [43] (c).

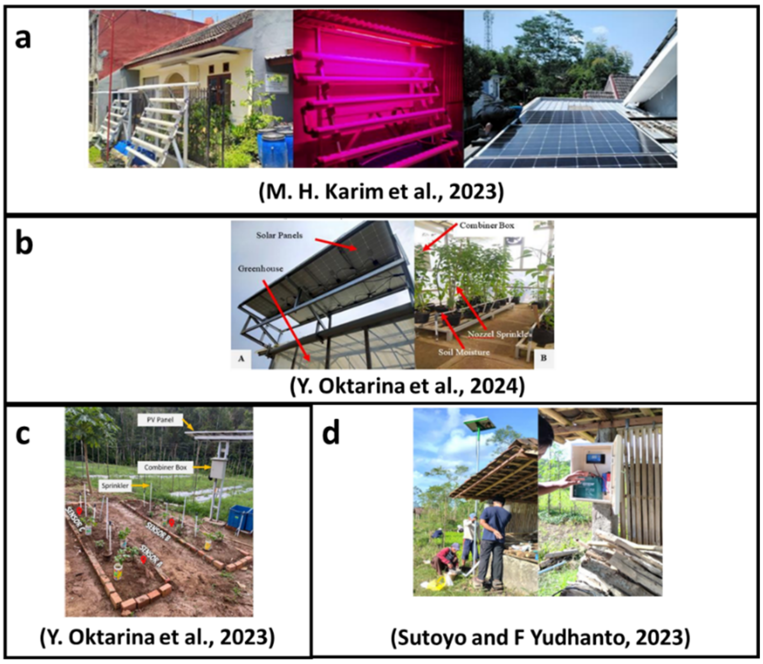

Figure 9. The agrivoltaics system supplies energy to indoor farming, hydroponic systems, greenhouse, and open crop systems for automatic irrigation and fertigation in Malang [42] (a), South Sumatera [44,46] (b,c), and Gunung Kidul [48] (d).

Most of the research papers on agrivoltaics in Indonesia, as shown in Figure 9, do not place solar panels on farms directly but use small-scale solar panels to supply electrical energy to open farms, indoor farms, greenhouses, and hydroponic systems. Actually, these systems are not an agrivoltaics system, as it is known globally, which places PV panels directly on agricultural land so that there is an interaction between the two systems. Even so, it shows the benefits of the electrical energy obtained from solar panels in agrivoltaics, which can be used for automatic irrigation and fertigation in smart farming systems by integrating IoT and various sensors to increase efficiency and reduce the use of labor [44,46–48]. Energy from solar panels is also utilized for energy needs in hydroponic systems, LED lights in indoor farming, aquaponics, and integrated pest management to reduce the use of pesticides. This can reduce the cost and use of electricity sourced from fossil fuels, making the agricultural system energy-independent, sustainable, and environmentally friendly [42].

Agrivoltaics systems were developed to improve land use efficiency due to the increasingly limited availability of land and prevent deforestation due to the clearing of new land for increased food and energy production. These systems can also provide mutual benefits for photovoltaic modules and agricultural crops. By reducing panels' temperature, particularly under warm climatic conditions, they can enhance PV efficiency, while simultaneously decrease crop evapotranspiration and thus lower irrigation requirements. In addition to these thermal and hydrological benefits, the placement of PV modules and the associated ground coverage ratio are critical design parameters that can significantly influence not only the microclimatic conditions but also the overall economic performance of agrivoltaics installations. Optimal configurations must therefore balance adequate light availability for crops with sufficient PV coverage to ensure that both agricultural productivity and energy generation remain economically viable.

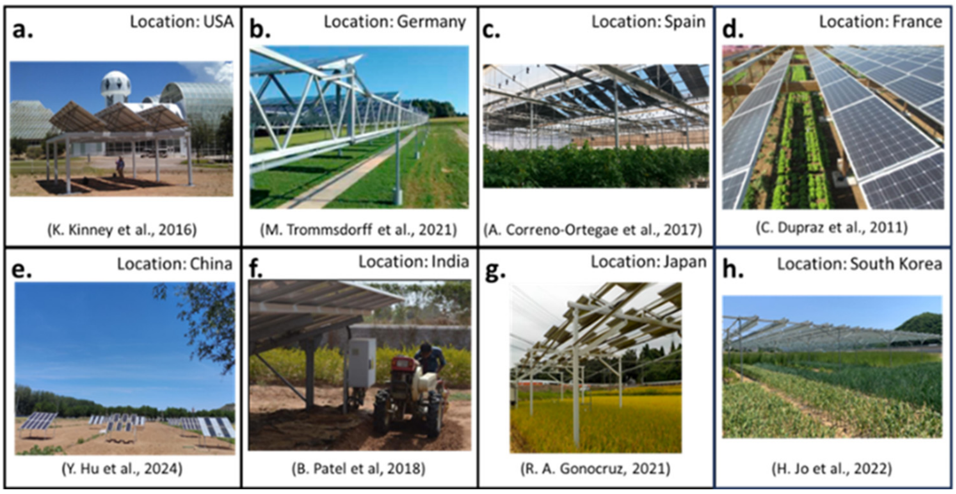

Figure 10. Overview of agrivoltaics facilities in some countries such as USA [69] (a), Germany [70] (b), Spain [71] (c), France [72] (d), China [73] (e), India [74] (f), Japan [75] (g), and South Korea [23] (h).

Solar panels are usually placed 2–4 m above the farm's surface depending on the height of agricultural equipment used in each country or according to applicable regulations [17,34,59]. The height of the solar panel above the farm is influenced by the size of the agricultural mechanization equipment used in the type of crop and the farm's location to ensure that agricultural activities can run properly [21]. Agricultural machinery usually used in Indonesia included two-wheeled tractors, four-wheeled tractors, combine harvesters, and rice transplanter[66,67]. In the list of machines, the largest one has maximum dimensions of 3 m high and 2.5 m wide, and this can be taken into consideration according to the explanation of the dimensions to consider [68]. The intended height of the solar panels can be seen in Figure 11 as dimension D, and an example of agricultural activities using agricultural machinery is shown in Figure 10f. The distance between rows or strings also needs to be considered to minimize the shadow effect on the agricultural crops below and the self-shading of PV panels between rows.

The fixed solar panel system in Figure 11 also shows several dimensions that need to be optimized in order to minimize negative impacts and optimize the production of electrical energy from PV panels. Tilt angle is the angle of the solar panel to the horizontal position, as in Figure 11 Dimension A where this angle depends on the location of the solar panel. For areas located in the southern part of the Earth, the angle will face north and vice versa. The angle will be greater if the location is closer to the South or North Pole. Stilt post distance is the distance between the poles where the solar panels are placed to accommodate agricultural machinery which has the same function as the D (PV panel height) dimension previously explained [17,21]. The distance between PV panels (C) and the row distance (E) are critical design parameters that directly affect both crop shading and PV energy output. A reduction in the PV panel distance (C) and row distance (E) minimizes shading but maximizes energy production by reducing the spacing between panels. However, when these distances are increased, the shading effect on crops is minimized, but it may result in a decrease in energy generation due to the wider spacing. The optimal configuration of these distances should be determined according to the specific goals of the system, such as prioritizing agricultural yield, energy production, or balancing both objectives for land use efficiency [59]. However, for the systems that only use solar panels as an electrical energy source for smart farming, hydroponics, or LED indoor farming activities, in which PV panels and crops are in an indirect physical combination, as described in the research conducted in Indonesia, this is not an agrivoltaics system, and the concept of dimension optimization will differ from the concept described in Figure 11.

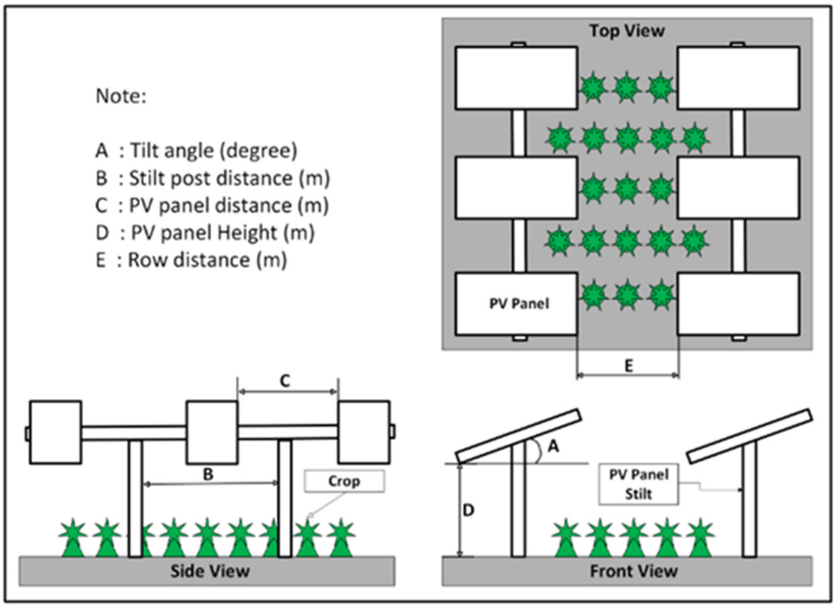

Figure 11. Typical configurations of agrivoltaics system.

3.4. Opportunities and challenges in applying agrivoltaics in Indonesia

Agrivoltaics presents a promising solution to the growing food-energy-water nexus challenge, offering economic, environmental, and agricultural benefits [22]. However, Dupraz (2023) highlights that the shading effect of PV panels can reduce photosynthetically active radiation, potentially leading to decreased crop yields, especially with high GCRs. The challenge lies in optimizing the system's design to balance energy production with agricultural productivity, ensuring that the benefits of agrivoltaics outweigh the potential negative impacts on crop growth [59]. In Indonesia, the adoption of agrivoltaics systems could significantly contribute to achieving renewable energy targets while supporting food security and rural electrification. However, addressing its technical, economic, and policy-related challenges is crucial for wider adoption. Future research should focus on optimizing agrivoltaics designs suitable for Indonesia's tropical climate, improving financial support mechanisms, and developing policies that encourage large-scale implementation [17]. By overcoming these obstacles, agrivoltaics can play a vital role in promoting sustainable development and energy transition in Indonesia.

Agrivoltaics presents significant opportunities and challenges across various aspects, as identified in multiple research papers. In summary, the opportunities and challenges of implementing agrivoltaics can be seen in Table 3 below.

Table 3. Opportunities and challenges in applying agrivoltaics in Indonesia.

Category	Opportunities	Challenges	References
Land efficiency	Increases land productivity by combining food and energy production	Balancing energy production and crop yield optimization	[17,19,21–23,26,33,36]
Water efficiency	Reduces evaporation and improves water use efficiency	Uneven water distribution due to PV panels	[21–23,36]
Economic benefits	Increases farmers' income through electricity sales and crop production	Economic feasibility depends on policy incentives	[5,17,19,21,36]
Energy security	Supports rural electrification and decentralized energy systems	Limited technological access and financing for small-scale farmers	[5,21,26]
Sustainability and climate change	Reduces carbon emissions and enhances crops' resilience to climate change	Long-term impacts on soil, water, and biodiversity require further research	[21,22,26,36]
System and technology optimization	Enhances efficiency through digital simulation and artificial intelligence	Complex optimization of panel density and orientation	[27,76]

Continued on next page

Category	Opportunities	Challenges	References
Crop resilience	Increases soil moisture and reduces heat stress on crops	Overly dense PV layouts prioritizing energy generation over agricultural needs leads to reduced crop yield due to excessive shading under PV installations.	[22,23,33]
Policy support	Government incentives and feed-in-tariff (FiT) promote agrivoltaics	Regulatory uncertainty and lack of legal standards for agrivoltaics land use	[12,26,36]
Initial investment cost	Some agrivoltaics systems have a shorter payback period (3 years) than conventional PV systems	High initial costs for infrastructure and integration with agricultural systems	[4,5,26]
Operational constraints	-	Limited access for farming equipment, regular PV panel maintenance required to remove dust and debris	[19,21,22,76]

One of the primary benefits of agrivoltaics is enhanced land use efficiency, as it enables the simultaneous production of food and energy [19,21]. Studies show that this system can increase land's productivity by up to 70% and optimize land resources by reducing competition between agriculture and renewable energy [22]. Dupraz emphasizes that sustaining high crop yields (>80%) generally necessitates maintaining a low ground coverage ratio (<25%), highlighting the influence of climate, crop type, and panel configuration. Overall, while agrivoltaics systems demonstrate substantial potential, their performance remains highly site-specific, warranting further location-specific investigation [59]. This is particularly relevant in Indonesia, where land availability for renewable energy development is often constrained by agricultural needs.

Indonesia, as a tropical country located along the equator, possesses abundant solar energy potential. According to data from the Ministry of Energy and Mineral Resources, the technical potential for solar energy in Indonesia is estimated to reach approximately 3,294 gigawatt-peak (GWp), reflecting a significant increase from the previously stated 207 GWp in 2021 and only about 911.5 MWp being utilized [77,78]. In alignment with its renewable energy roadmap, Indonesia aims to install 32 GW of solar capacity by 2030, with projections reaching 421 GW by 2060, reinforcing the strategic importance of solar power in the national energy transition [79].

This enormous potential is demonstrated through data from the World Bank Group and Solargis on the global horizontal irradiation (GHI) and PV power potential (PVOUT) maps, as shown in Figure 12, which provide a detailed assessment of solar resources across the country. The GHI map presents long-term average solar radiation data from 2007 to 2018, with values ranging from 1,314 to 2,191 kWh/m² annually. The highest GHI levels (5.2–6.0 kWh/m² per day) are concentrated in Nusa Tenggara, southern Java, southern Sulawesi, and parts of Papua. Southern Java and southern Sulawesi are already known as the center of agricultural industry in Indonesia;

specifically they have abundant rice fields, which make this area a strong candidate for the application of agrivoltaics in Indonesia. Highlighting areas with strong agrivoltaics potential.

Agrivoltaics also provides economic benefits, such as increased farm income from dual revenue streams, namely crop production and electricity generation. Some studies estimate that farm revenues can increase by over 30% through the adoption of agrivoltaics [19]. In Indonesia, this could support smallholder farmers, who constitute approximately 93% of the country's agricultural workforce, by offering an additional source of income [17,64]. Additionally, vegetation management beneath solar panels can be efficiently handled with grazing animals, particularly sheep. This approach, known as solar grazing, reduces maintenance costs and enhances soil health, while also offering a supplementary income stream [21]. It has also been highlighted that integrating livestock into agrivoltaics systems improves land use efficiency and supports multifunctional farming, which is especially beneficial for smallholders [80].

Another critical advantage is water conservation, as shading from solar panels reduces water evaporation, leading to improved water productivity, particularly in arid and drought-prone regions. Certain studies report water savings of 14–29%, which is crucial for sustainable farming [22]. This is particularly beneficial for regions like East Nusa Tenggara and Central Java, where seasonal droughts often threaten agricultural productivity [81,82]. Drought usually occurs during dry seasons in areas with poor irrigation access, especially when El Niño strikes many regions in Indonesia, including Java, causing long dry seasons and below-normal rainfall [82–84]. Meanwhile, the East Nusa Tenggara region is characterized by dry conditions, with the dry season lasting longer than the wet season [81]. Under these conditions, the presence of plants also has the potential to reduce soiling losses on solar PV modules, thereby preventing a decrease in solar panels' efficiency [85]. However, during the rainy season, uneven water distribution from solar panel runoff can lead to soil erosion and localized wet/dry zones, highlighting the need for optimized irrigation strategies [19]. To address these challenges effectively, agrivoltaics water management must be region-specific, incorporating local climate data, soil characteristics, and farming practices to ensure both agricultural productivity and system's sustainability.

From an energy perspective, agrivoltaics enhance renewable energy efficiency by improving the cooling effect on solar panels, which can boost PV efficiency by 1–3% annually [22]. Moreover, agrivoltaics contributes to decarbonization efforts by reducing reliance on fossil fuels, lowering greenhouse gas emissions, and supporting Indonesia's commitment to net zero emissions by 2060 [7,77].

Despite its numerous benefits, agrivoltaics faces several challenges. One of the key concerns is reduced crop yield, as shading from PV panels can limit sunlight exposure, affecting the growth of shade-intolerant crops [21]. Studies highlight that solar radiation can be reduced by about one-third, potentially impacting agriculture [76]. In Indonesia, this issue could be significant for crops such as rice, maize, and soybeans, which require full sunlight for optimal growth. However, agrivoltaics may benefit shade-tolerant crops such as coffee, tea, and certain vegetables, which could be prioritized for cultivation under PV structures.

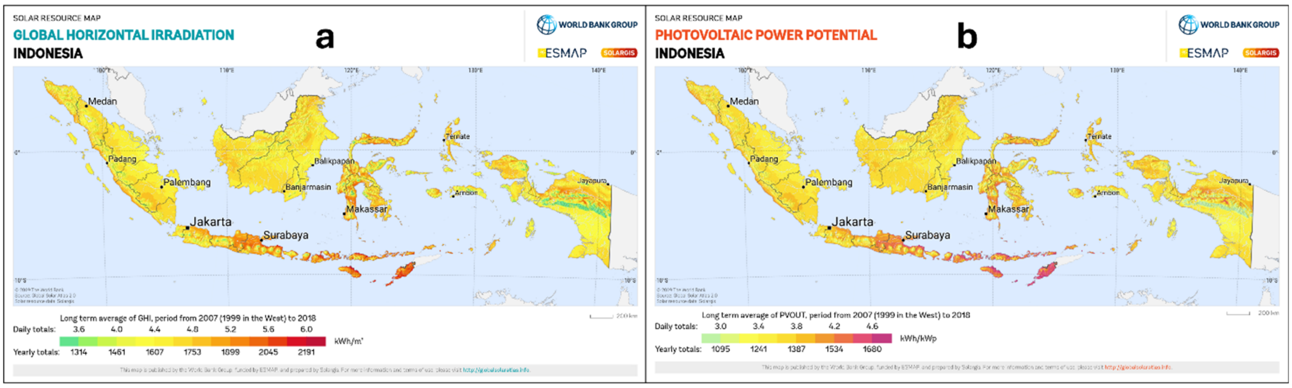

Figure 12. Map of global horizontal irradiation (a) and PV power potential (b) in Indonesia (source: globalsolaratlas.info).

Another major challenge is the high initial investment cost required for installing elevated PV structures and modifying farming systems. Some reports indicate that agrivoltaics installations can be 30% more expensive than conventional solar farms, making their financial feasibility dependent on subsidies and policy incentives [26]. In Indonesia, where solar energy investment still faces policy uncertainty and financing limitations, the high upfront cost remains a major barrier.

Additionally, crop selection plays a crucial role in the successful implementation of agrivoltaics, as certain plant species exhibit greater tolerance to shading than others. In the context of Indonesia, it is essential to choose crops that are well-suited to tropical climates, offer added economic value, and demonstrate resilience to the shading effect. Examples include tomato, garlic, onion, and bok choy, which can maintain a total yield above 80%. To ensure yields remain within a moderate range of 80–100%, several studies recommend maintaining a GCR or shading ratio of approximately 30% [23]. By adhering to this maximum GCR threshold, the negative impact of shading on rice, which is known to be highly sensitive to reduced light, can be minimized, thereby reducing the decline in harvest yield [23,33,59].

On a broader scale, policy and regulatory uncertainty hinder the deployment of agrivoltaics, particularly in countries without clear frameworks for land use and renewable energy incentives [36,86]. In Indonesia, regulatory complexities, especially in land permit and grid connection policies, pose significant challenges for agrivoltaics developers [36]. These issues are compounded by limited access to technology and financing among small-scale farmers, which restricts adoption in rural areas and exacerbates inequality in the benefits of agrivoltaics [36,87–89]. As Hu [86] highlights, large-scale agrivoltaics projects often marginalize smallholders through land appropriation and exclusion from project participation, underscoring the need for inclusive, locally adapted models. Environmental factors also play a role; for instance, dust accumulation on solar panels, particularly in volcanic regions such as Sumatra and Java, can reduce energy efficiency and increase maintenance demands [26]. Addressing these technical, financial, and policy barriers is essential to ensure agrivoltaics can be a viable and equitable solution for sustainable agriculture and energy production in Indonesia.

4. Conclusion and recommendations

Agrivoltaics presents a promising and innovative approach to Indonesia's interconnected food, energy and water challenges. By integrating solar PV system generation with agricultural activities on the same land, agrivoltaics system enhances land use efficiency, increases farmers' income, and improves water productivity. This dual use model aligns with Indonesia's goals for renewable energy expansion and rural development. However, its viability depends on overcoming key barriers such as regulatory complexity, limited access to financing and technology for smallholders, and the need for supportive policy frameworks. While these challenges are not unique to agrivoltaics and are shared with broader solar PV deployment, agrivoltaics offers distinct advantages in agricultural regions, particularly in tropical zones with high solar irradiance, by enabling co-benefits for food production and rural electrification. With targeted government support and inclusive implementation strategies, agrivoltaics could become a strategic pathway toward a resilient and low-carbon energy future in Indonesia. Despite its vast potential, the widespread adoption of agrivoltaics in Indonesia faces several key challenges. Technical limitations, such as optimizing systems' configurations for tropical climatic conditions, maintaining a balance between energy generation and agricultural productivity, and managing the high initial capital investment, pose significant barriers. Furthermore, regulatory and policy uncertainties, along with limited access to appropriate technologies and financing options, particularly for smallholder farmers, hinder large-scale deployment.

Nonetheless, Indonesia's expansive agricultural landscape presents a strategic opportunity to harness solar energy for dual purposes: Enhancing food production while accelerating the transition to clean energy. To fully realize this potential, it is essential to prioritize the development of agrivoltaics systems tailored to Indonesia's tropical environment, establish robust financial support mechanisms, and formulate coherent policies that promote adoption across various scales.

In parallel, there is a need to encourage increased research on agrivoltaics technology in Indonesia, which remains very limited, in order to support its appropriate implementation and optimize both solar power generation and agricultural productivity. This could enhance the dual optimization of solar energy utilization and agricultural production, in line with the growing global demand for sustainable food and energy sources. Agrivoltaics holds the potential to play a transformative role in Indonesia's development strategy by advancing renewable energy targets and contributing to the national ambition of achieving net zero emissions by 2060. By addressing the technical, economic, and institutional barriers, agrivoltaics can unlock new opportunities for Indonesia's agriculture and energy sectors, driving inclusive and resilient growth.

Further research should focus on crop compatibility with Indonesia's strategic crops, such as potato, tomato, and garlic, based on data from BPS-Statistics Indonesia and the Directorate General of Horticulture, which have shown positive to moderate effects under agrivoltaics systems. In total, there are 18 strategic horticultural products that could be the object of research that would impact the availability of the most needed crops in Indonesia while reducing fossil energy dependence. In addition, there is still little research that discusses the effect of agrivoltaics on solar panels related to the decrease in temperature that can maintain the efficiency of solar panels.

Use of AI tools declaration

The authors declare that no Artificial Intelligence (AI) tools were used in the preparation of this paper.

Acknowledgments

This research was supported by the Institute of International Research and Development (IIRD) at Kyungpook National University (KNU) through the Korea International Cooperation Agency (KOICA) Scholarship Program. The authors express their sincere gratitude for the academic support and guidance provided through this program, which has played a vital role in the successful completion of this work.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contributions

A.A.: conceptualization, formal Analysis, data duration, methodology, software, visualization, writing—original draft, writing—review & editing, N.C.M.: data curation, investigation, methodology, writing—original draft, Z.A.F.; data curation, formal analysis, investigation, validation, writing—original draft, A.F.: data curation, formal analysis, investigation, visualization, S.L.: conceptualization, project administration, resources, supervision, validation, writing—review & editing. All authors have read and agreed to the published version of the manuscript.

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