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THE ECONOMICS OF AGRIVOLTAIC SYSTEMS: A MAPPING REVIEW

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Abstract

Agrivoltaic systems (AVS) combine solar PV technology with agriculture, offering a dual-use solution to land-use conflicts and energy needs. While environmental and technical benefits are well-studied, economic viability remains less explored. This review analyzes 53 peer-reviewed studies using metrics like ROI, CBR, and IRR. Results show fixed tilt and bifacial systems offer strong economic potential, while elevated and tracking systems often need policy support. Key challenges include high upfront costs, inconsistent profitability, and limited long-term financial data. Standardized metrics and deeper economic analyses are needed to support AVS adoption and policy development.

Keywords: Agrivoltaic systems, economic impacts, profitability, renewable energy, agriculture

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INTRODUCTION

Renewable energy, particularly solar photovoltaics (PV), presents a viable pathway to mitigate carbon emissions by reducing reliance on fossil fuels. Among renewable sources, solar PV has shown significant potential in lowering global greenhouse gas emissions and is expected to contribute substantially to the global energy mix. By 2026, renewable energy sources are projected to account for over one-third of total global electricity generation, with solar PV leading at an anticipated 37% growth (IEA, 2024). Solar energy's role in achieving net-zero emissions by 2050 is essential, as it reduces fossil fuel dependence and enhances energy production and storage capacity (Ali et al., 2024; Yusoh et al., 2023).

Despite its environmental benefits, the expansion of solar energy presents land-use challenges, as solar farms require large, open spaces often situated in agricultural areas to minimize development costs (Goh et al., 2024). This overlap creates competition for land, impacting local economies, food security, and biodiversity (Ahmad et al., 2024; Muhammad Nor et al., 2024; Yusoh et al., 2024). Projections suggest that global cropland may shrink by 50 to 650 million hectares by 2100 due to infrastructure expansion, urbanization, and environmental degradation, exacerbating the need for integrated solutions (Malu et al., 2017).

Agrivoltaic systems (AVS), which combine solar PV with agricultural activities on the same land, offer a promising dual-use solution, enhancing both energy production and agricultural yields. Research from the United States, Europe, and India indicates that AVS can diversify income, bolster economic resilience against weather-induced revenue fluctuations, and potentially increase farmers' net earnings (Cuppari et al., 2021). However, AVS adoption remains limited due to high initial costs and the complexities of adapting systems to varied climates, crop types, and market conditions (Jain et al., 2021).

While the current literature extensively addresses the technical, environmental, and socio-ecological benefits of agrivoltaics, there is a notable gap in assessing its economic feasibility and financial outcomes. Sirmik et al. (2023) and Mamun et al. (2022) provide reviews focusing on environmental sustainability, design, and landscape integration, while Favi et al. (2024) emphasize agrivoltaics' benefits across the water-energy-food-environment nexus in West Africa. Widmer et al. (2024) discuss AVS's potential for dual food and electricity production, and Zheng et al. (2024) explore the trade-offs between agricultural output and energy generation. However, these studies do not examine AVS's economic viability, including metrics like cost-effectiveness, return on investment, or regional financial scalability.

This review makes two unique contributions to the economic planning and renewable energy literature. First, it is the earliest systematic mapping review dedicated specifically to agrivoltaic economics, providing a structured synthesis

of financial feasibility across system configurations. Second, by consolidating global evidence into economic knowledge clusters, this review offers a foundation for planners and policymakers to evaluate agrivoltaics as a dual-use land strategy within national and regional development frameworks

Objective of the Review

The objective of this systematic map is to identify, catalogue, and explore the economic aspects of agrivoltaic systems, with a focus on evaluating their financial feasibility, profitability, cost structures, and the effectiveness of policy incentives. This review will consolidate existing knowledge on the economic impacts of agrivoltaic systems, focusing on cost-benefit analyses, financial performance, and economic implications across different regions and contexts. By highlighting promising research areas and identifying gaps in the literature, this review aims to provide a foundation for scientific, philanthropic, governmental, and non-governmental organizations to strategically allocate resources towards sustainable agrivoltaic initiatives. Through this synthesis, the review will also outline potential agrivoltaic interventions where economic research is currently limited, supporting informed investment in programs, policies, and research that contribute to the sustainability and scalability of agrivoltaics.

The systematic map aims to answer the following primary research question: “What evidence exists on the economic impacts of agrivoltaic implementation?” The components of this primary research question are summarized in Table 1.

Table 1: Components of primary research questions

Component	Description
Population	Global, with a focus on studies conducted across diverse geographical regions and agricultural contexts to understand the economic implications of agrivoltaic systems worldwide.
Intervention	Implementation of Agrivoltaic Systems (AVS), combining solar PV with agricultural practices to allow for dual land use, focusing on systems aimed at enhancing both energy and crop production.
Comparison	Not required; however, studies with comparisons to conventional farming, traditional solar farms, or other renewable energy methods will be included for additional insights.
Outcome	Economic impacts, including cost-effectiveness, return on investment (ROI), financial scalability, income diversification, cost-benefit analysis, and implications for local and regional economic resilience.

RESEARCH METHODOLOGY

The systematic map protocol has been developed in accordance with the PRISMA 2020 guidelines for systematic maps (Page et al., 2021) and follows the PRISMA 2020 reporting standards to ensure transparency and rigor in the synthesis process

(see Supplementary Material 1). The flow of the study selection is shown in Figure 1.

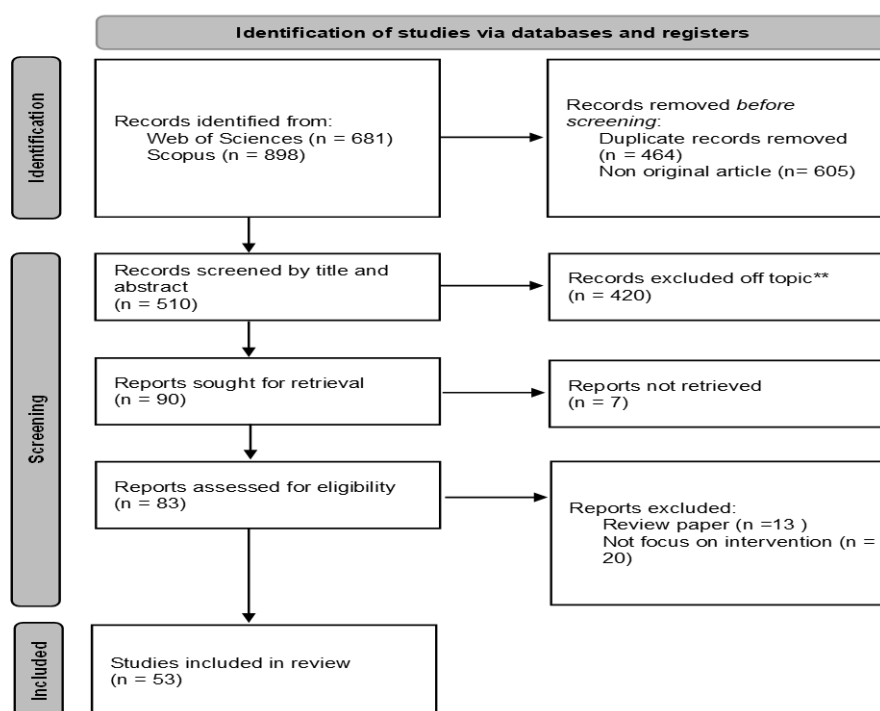


Figure 1: PRISMA flow diagram detailing the screening, eligibility, exclusion and inclusion criteria after a keyword search u

Bibliographic Databases

The literature search for this systematic map was conducted using two primary bibliographic databases: Web of Science and Scopus, both accessed through Universiti Teknologi MARA on 11th October 2024. In Web of Science, the Science Citation Index Expanded (SCI-EXPANDED) section of the Core Collection was searched, focusing on the “topic” (TS) field, which includes titles, abstracts, keywords, and “KeyWords Plus” (terms automatically generated from cited references). In Scopus, article titles, abstracts, and keywords were searched using the predefined search string detailed below, covering all available years.

Grey literature (non-peer-reviewed publications) was excluded from the review to maintain consistent scientific rigor and due to the lack of a systematic retrieval method for these sources. All searches were conducted in English, and only English-language publications were included, as English is the primary language of the reviewers. Search results were exported into an Excel spreadsheet

and reference management software, where duplicates were removed prior to analysis.

Search Terms

The search string "TS=((agrivoltai*) OR (agri-voltai*) OR (agriphotovoltai*) OR (agri-photovoltai*) OR (agrovoltai*) OR (agro-voltai*) OR (agrophotovoltai*) OR (agro-photovoltai*) OR (agrisolar) OR ("dual-use solar") OR ("solar farming") OR ("solar sharing*") OR ("PV agriculture*") OR ("dual land us*") OR ("photovoltaic greenhouse*") OR ("agriculture* photovoltaic*") OR ("greenhouse* photovoltaic*") OR ("flexible photovoltaic panel*"))" was developed specifically to encompass a broad range of terms associated with agrivoltaic systems. This inclusive search strategy was designed to capture the full scope of agrivoltaic studies, acknowledging that economic outcomes and impacts are not always directly stated in titles or abstracts. By avoiding restrictive filters, this approach maximizes the likelihood of identifying studies with relevant economic insights that might otherwise be overlooked.

Article Screening and Study Eligibility Criteria

Screening Process

The screening process for the systematic map was conducted in two stages: (i) title and abstract screening and (ii) full-text review following (Azzeri et al., 2020). At each stage, studies were evaluated against predefined eligibility criteria. The first stage involved reviewing titles and abstracts, with studies meeting the inclusion criteria proceeding to the second stage for full-text review. Articles with unclear relevance at the first stage were also included for further evaluation at the full-text level to ensure no potentially relevant studies were excluded prematurely. A detailed record of included and excluded articles was maintained at each stage, with reasons for exclusion at the full-text stage documented in an additional file.

To enhance consistency and accuracy, the screening process was conducted independently by two reviewers. A Kappa test was performed to assess inter-rater reliability. A random sample of 100 articles was screened independently by each reviewer, and the results were analyzed using Cohen's Kappa test (Cohen, 1960). Agreement levels were classified as "substantial" ($K=0.61-0.80$) or "almost perfect" ($K=0.81-1.0$). Discrepancies were resolved through discussion, ensuring consensus before the full screening process commenced. To maintain objectivity, assessments of publications authored or co-authored by review team members were referred to an independent reviewer.

Eligibility Criteria

Relevant Types of Intervention: The review focused on studies investigating agrivoltaic systems, defined as interventions combining solar photovoltaic (PV) technology with agricultural practices on the same land to achieve dual land use. Only studies explicitly examining the implementation, design, or adaptation of agrivoltaic systems were included. Articles not directly related to agrivoltaic systems were excluded. Articles with a primary focus on environmental or social benefits without detailed economic analysis and lack primary economic data or do not address economic feasibility are excluded.

Relevant Types of Outcomes: The primary outcome of interest was the economic impact of agrivoltaic systems. Studies were included if they reported on economic outcomes such as cost-effectiveness, return on investment (ROI), income diversification, financial scalability, or contributions to economic resilience. Non-economic outcomes were excluded unless they provided supplemental insights into the financial viability of agrivoltaic systems.

Study Design: The review prioritized primary research articles and excluded opinion pieces, as they lacked primary data. Studies focusing on solar panel development, energy production, or social perception without economic analysis were also excluded. A total of 52 publications met the inclusion criteria and were included in the review.

Study Quality Assessment

A structured quality assessment checklist was applied to ensure the inclusion of high-quality studies. The checklist evaluated eight critical aspects, including study details, participant characteristics, interventions, data collection methods, and findings analysis. Articles were scored based on whether they met the criteria: 2 points for full compliance, 1 point for partial compliance, and 0 points for non-compliance. An aggregated quality score was calculated for each article, providing an overall assessment of its reliability and validity.

Data Coding Strategy

Metadata extraction and coding were performed on all studies passing the inclusion/exclusion criteria at the full-text screening stage. Two reviewers independently conducted the coding, with consistency verified through Kappa test analysis. A random sample of 10 articles was independently coded, and discrepancies were resolved until a substantial agreement ($\text{Kappa} > 0.61$) was reached. If data were insufficient or unclear, authors were contacted for clarification via email. Articles were excluded if authors did not respond or provide the necessary details.

Bibliographic Information

Each article was assigned a unique Study ID for easy reference, and each reviewer had a unique Coder ID to track individual assessments. Citation information was meticulously recorded to ensure accuracy and traceability.

Study Design

The systematic map aimed to comprehensively evaluate the economic implications of agrivoltaic systems. For each article, key details were recorded, including the study objectives, geographic focus, type of agrivoltaic system analyzed, and the economic methods employed. Findings were synthesized to highlight trends, gaps, and insights into the financial feasibility and market potential of agrivoltaic systems. This structured approach ensured transparency, reproducibility, and a comprehensive understanding of the economic dimensions of agrivoltaic systems. The key elements of the systematic map included the following:

- **Citation Metrics:** Citation counts and average citations per year were analyzed to identify influential studies and trends in agrivoltaic economic research.
- **Geographic Distribution:** The review identified leading countries contributing to agrivoltaic economic research.
- **Economic Performance and Profitability:** Financial metrics such as Net Present Value (NPV), Internal Rate of Return (IRR), Levelized Cost of Electricity (LCOE), Payback Period (PBP), and benefit-cost ratios were assessed to evaluate economic performance.
- **System Configurations:** Economic outcomes for various agrivoltaic configurations, including bifacial, fixed-tilt, elevated, and dynamic systems
- **Knowledge Cluster Analysis:** Studies were categorized into knowledge clusters focusing on economic viability, crop productivity, and environmental benefits, providing insights into the distribution of research within these areas.

Bibliographic Information

Each article in the review was assigned a unique Study ID, providing a numeric identifier for easy reference. Each reviewer involved in the coding process was assigned a unique Coder ID to track individual assessments. Citation information for each article was recorded to ensure accurate referencing and traceability within the systematic map.

Study Review and Presentation

The final systematic map included summary figures and tables detailing the study characteristics of all identified evidence. Heat maps were generated to cross-tabulate two key variables, illustrating the volume of evidence (number of studies) within each cell. These heat maps highlighted various combinations of variables, specifically (i) knowledge clusters and (ii) key research focus areas, with knowledge clusters represented as columns and research focuses as rows. This approach effectively identified knowledge gaps—underrepresented subtopics requiring further primary research—and knowledge clusters, which are well-represented subtopics suitable for comprehensive synthesis. The analysis revealed key research focus areas, including standardized economic metrics, long-term financial performance, crop compatibility studies, impacts on soil and water resources, quantification of environmental impact, and adaptation to climate variability. Knowledge clusters encompassed themes such as economic viability, crop productivity, and environmental benefits. Based on these findings, recommendations were provided to guide future research priorities, advancing the field of agrivoltaics.

ANALYSIS AND DISCUSSION

Evolution of Published Studies

The search, as detailed in the methodology section, retrieved a total of 53 publications with an h-index of 18. These publications have accumulated 1,031 citations, resulting in an average citation rate of 19.45 citations per article.

Figure 2 illustrates the trajectory of economic research on agrivoltaic. The publication data on shows a clear upward trend, with low initial output (2 publications each in 2017 and 2020) rising to 7 in 2021, 11 in 2022, and peaking at 17 in 2023. The overall growth reflects increasing interest in the economic feasibility and market potential of agrivoltaic systems. This trend highlights agrivoltaics as an emerging focus in sustainable energy and agricultural economics, with researchers prioritizing its financial viability and dual benefits for energy and agriculture.

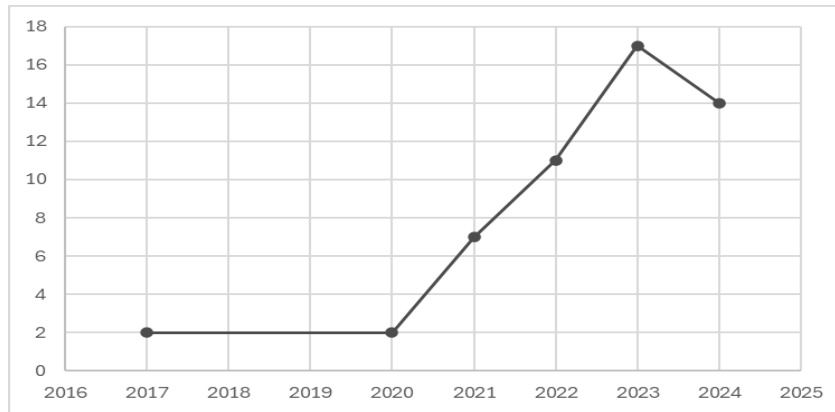


Figure 2: Number of research articles regarding economic research on agrivoltaic

The top five most-cited articles on the economic research of agrivoltaic systems reveal critical insights into the potential of this dual land-use approach. Schindele et al. (2020), (178 citations, 35.6 per year), demonstrate that agrophotovoltaic systems have higher levelized costs of electricity compared to ground-mounted PV systems but can yield favorable economic outcomes for specific crops like potatoes. Agostini et al. (2021) (125 citations, 31.25 per year), highlight Agrovoltaco® systems in Italy, which achieve comparable costs to conventional photovoltaics and provide additional benefits such as improved water efficiency and land-use optimization. Malu et al. (2017) (125 citations, 15.63 per year), show a 15-fold increase in the economic value of grape farms through agrivoltaic implementation, maintaining grape yields while generating significant electricity for rural electrification. Gonocruz et al. (2021) (46 citations, 11.5 per year), find that rice yields can sustain 80% of normal levels under optimal shading conditions, potentially meeting 29% of Japan's electricity demand. Feuerbacher et al. (2021) (35 citations, 8.75 per year), introduce the FEADPLUS framework, emphasizing that profitability is highly dependent on photovoltaic parameters and farm-specific trade-offs, such as shading effects reducing yields by up to 70%.

These studies collectively highlight the significant economic and environmental benefits of agrivoltaic systems, including improved land-use efficiency, enhanced crop protection, and renewable energy generation. However, they also emphasize challenges such as higher costs compared to traditional photovoltaic systems, the necessity of crop-specific suitability assessments, and the need for tailored policy interventions. The findings by Schindele et al. (2020) and Feuerbacher et al. (2021) suggest that profitability is often contingent on specific crop types, with low-value crops like cereals being more suitable for agrivoltaics than high-value crops such as vegetables. Meanwhile, the studies by

Malu et al. (2017) and Gonocruz et al. (2021) underscore the viability of agrivoltaic systems in addressing energy and food security in land-scarce regions, particularly for staple crops like rice. Agostini et al. (2021), highlight the broader sustainability contributions of agrivoltaic systems, aligning with global climate and energy goals. Nonetheless, further research is needed to refine cost structures, optimize system designs, and evaluate long-term impacts to support broader adoption of this promising technology.

Table 2: Citation metrics of the top 5 most-cited articles in agrivoltaic economic research

Title	Author	Total Citations	Average/Year
Implementation of agrophotovoltaics: Techno-economic analysis of the price-performance ratio and its policy implications	Schindele et al. (2020)	178	35.60
Innovative agrivoltaic systems to produce sustainable energy: An economic and environmental assessment	Agostini et al. (2021)	125	31.25
Agrivoltaic potential on grape farms in India	Malu et al. (2017)	125	15.63
Analysis of the Rice Yield under an Agrivoltaic System: A Case Study in Japan	Gonocruz et al. (2021)	46	11.50
An analytical framework to estimate the economics and adoption potential of dual land-use systems: The case of agrivoltaics	Feuerbacher et al. (2021)	35	8.75

Economic Profitability

Figure 3 categorizes the profitability of agrivoltaic systems (AVS) into four levels: highly profitable, moderately profitable, moderately profitable with support, and not profitable without support. The evidence shows clear regional variations driven by crop type, solar resource availability, technology choice, and policy environments. In Germany, profitability is generally moderate and heavily dependent on subsidies, crop selection, and strong policy support (Trommsdorff et al., 2023; Jürkenbeck and Schulze, 2024). Although AVS can enhance electricity production and offset farm infrastructure costs such as hail nets, high capital expenditure remains a constraint. Studies such as Schindele et al. (2020) and Feuerbacher et al. (2022) show that profitability varies widely across crops, with high-value crops like strawberries benefiting more from shading than cereals such as winter wheat. Additional work by Feuerbacher et al. (2021) and Sponagel et al. (2023) indicates that potatoes can generate economic gains under AVS, although converting more than 10 percent of arable land may slightly reduce agricultural gross margins. Overall, AVS viability in Germany relies on economies of scale and targeted policy tools, including feed-in tariffs that compensate for yield reductions and higher structural costs.

By contrast, India demonstrates consistently strong economic potential, with most systems classified as highly or moderately profitable. Favourable climatic conditions, low Levelized Cost of Energy (0.039 USD/kWh), and payback periods ranging from 6 to 9.5 years contribute to this performance (Anusuya et al., 2024). Innovative models such as blockchain-enabled grapevoltaic farms generate significant revenues for both farmers and system operators (Kumar and Chopra, 2023). Studies by Giri et al. (2023) highlight high Land Equivalent Ratios (LER) of up to 1.73 and benefit-cost ratios of 1.71, particularly under the KUSUM programme. Poonia et al. (2022) further show that strategic crop selection and full-density PV designs can deliver strong internal rates of return. The findings align with earlier results by Malu et al. (2017), which emphasize the importance of tailored feed-in tariffs and crop-specific planning to achieve highly profitable outcomes.

Other countries also show promising economic potential. In Vietnam, AVS installed on rice farms can generate profits up to 115 times higher than traditional rice cultivation (Ahmed et al., 2022). Pakistan demonstrates strong feasibility for crops such as potatoes and wheat, supported by favourable feed-in tariffs and policies that offset installation costs, enabling high productivity and increased rural income (Alam et al., 2023).

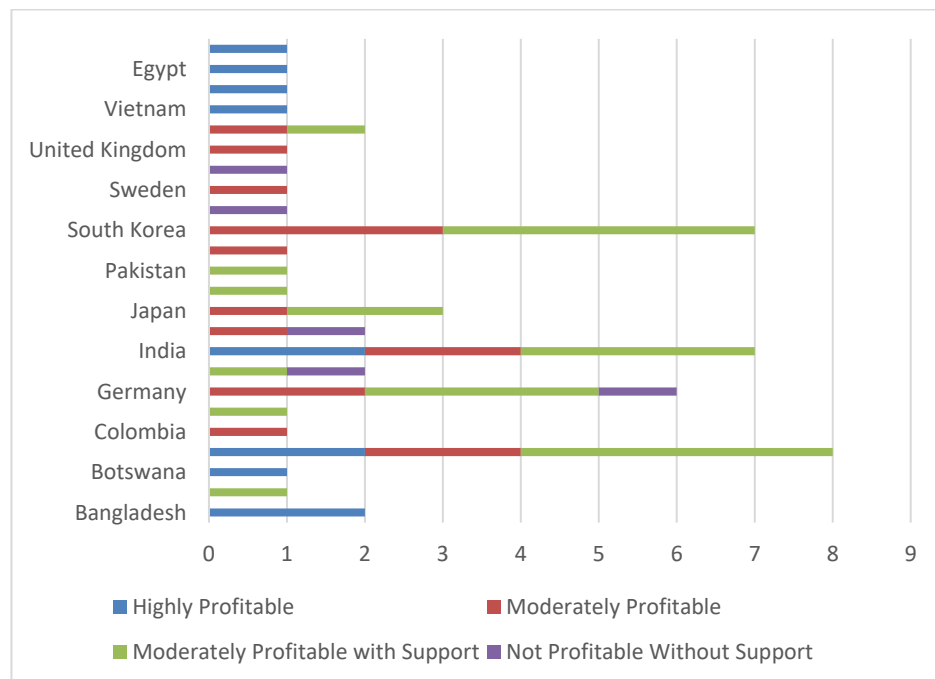


Figure 3: Profitability assessment of agrivoltaic systems across various countries

Figure 4 illustrates the profitability assessment of various agrivoltaic system configurations, categorized into five types: bifacial systems, dynamic and tracking systems, elevated systems, fixed-tilt systems, and portable and modular systems. The results are presented across four profitability categories: highly profitable, moderately profitable, moderately profitable with support, and not profitable.

The literature identifies Fixed-Tilt Systems as a highly profitable agrivoltaic configuration. These systems optimize dual land use by balancing solar energy production and crop yields through effective shading and spacing management. Their simple design minimizes maintenance costs, enhancing economic viability. Morena et al. (2021) and Gonocruz et al. (2021) demonstrated that Fixed-Tilt Systems sustain agricultural productivity while achieving high net present values. In contrast, Chalgyrbayeva et al. (2022), Ji et al. (2024), and Xue (2017) reported that Vertical or Overhead-Tilt configurations exhibit limited profitability without substantial financial or policy support. While these configurations offer advantages such as increased land-use flexibility and enhanced energy output in specific conditions, their higher installation costs and operational complexity often undermine their economic feasibility.

Bifacial Systems display balanced profitability across diverse environmental and economic conditions. Ahmed et al. (2022) and Hwang and Lee (2024), found that bifacial systems enhance energy generation by 20–35% through dual-side sunlight capture, improving land-use efficiency and lowering the levelized cost of energy. Chae et al. (2022) and Kim et al. (2023), report successful application in rice and broccoli cultivation, maintaining over 80% of conventional rice yields under 32% shading while optimizing energy production. Anusuya et al. (2024) highlight that the payback period for bifacial systems can exceed seven years, though this is significantly reduced under favorable financial mechanisms, such as subsidies or feed-in tariffs. Hwang and Lee (2024) emphasize that profitability improves in regions with high solar irradiance or strong policy incentives.

Portable and Modular Systems are the least represented among agrivoltaic configurations, with most installations classified as "moderately profitable" or "not profitable." Giri and Mohanty (2022) note that these systems offer flexibility and adaptability to diverse settings, making them suitable for small-scale or experimental applications. However, Zhang et al. (2023) and Giri and Mohanty (2022) highlight scalability challenges due to higher per-unit costs and logistical complexities. For example, a 0.675 kWp portable system was reported to have a payback period of 9.49 years, making it less competitive than larger, fixed systems.

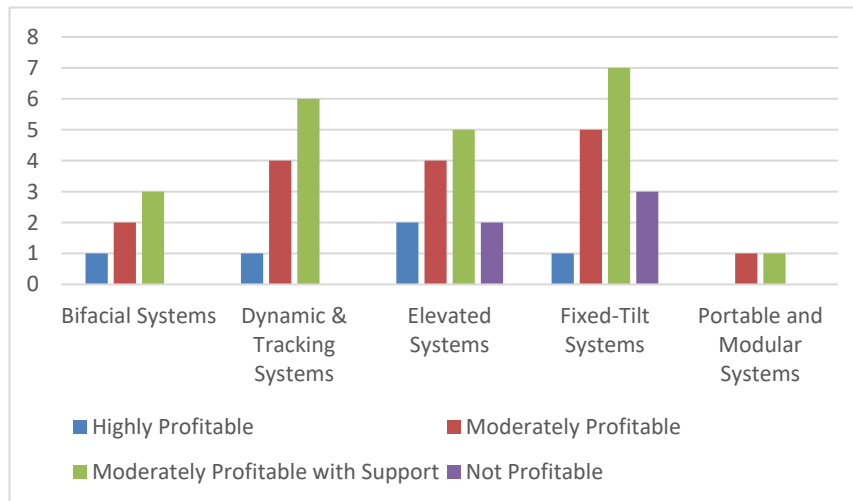


Figure 4: Profitability assessment of various agrivoltaic system configurations

The heatmap visualizes research distribution across three primary knowledge clusters: Economic Viability, Crop Productivity, and Environmental Benefits, with respective coverage of 92%, 79%, and 54%. Economic Viability is the most extensively explored, focusing on Standardized Economic Metrics and Long-Term Financial Performance, while Crop Compatibility Studies remain unaddressed in this cluster.

Under Economic Viability, researchers emphasize financial feasibility and sustainability. Cuppari et al. (2021) and Chalgynbayeva et al. (2022), used metrics such as cost-benefit ratios and revenue volatility to assess agrivoltaic systems. Feuerbacher et al. (2022) highlighted the importance of economies of scale, Campana et al. (2024) reported a 30-fold profitability increase in northern climates, and Willockx et al. (2023) demonstrated stable revenue generation through advanced system designs.

For Crop Productivity, the primary focus is on Crop Compatibility Studies, exploring how different crops adapt within agrivoltaic systems. Gonocruz et al. (2021) showed that shading levels of 27–39% maintained 80% of rice yields, meeting Japanese agricultural standards. Zheng et al. (2021) introduced the Even-lighting Agrivoltaic System (EAS), achieving a Land Equivalent Ratio (LER) of 1.64 and improving lettuce quality by increasing soluble sugars by 72%. Willockx et al. (2023) found that dynamic trackers outperformed fixed bifacial systems in sugar beet cultivation without affecting yields. Zhang et al. (2023) proposed spectral-splitting agrivoltaics, selectively transmitting light for crop growth and increasing biomass by 13%. However, limited research addresses Adaptation to Climate Variability within this cluster.

In Environmental Benefits, key themes include Quantifying Environmental Impact and Adaptation to Climate Variability, emphasizing agrivoltaics' potential in mitigating climate change and enhancing ecosystem resilience. Sponagel et al. (2024) estimated that adopting agrivoltaic systems on 1–5% of arable land in Baden-Württemberg could reduce greenhouse gas emissions by up to 5.9 million metric tons of CO₂ equivalent. Mo et al. (2023) showed that agrivoltaics optimized energy efficiency and supported climate-smart agriculture by reallocating sunlight to energy production while maintaining crop yields. Al-Amin et al. (2024) reported that agrivoltaics in Bangladesh reduced renewable energy payback periods and improved land-use efficiency.

CONCLUSION

In conclusion, while agrivoltaic systems demonstrate significant potential for economic and environmental benefits, their scalability and sustained financial viability require further exploration. By addressing the identified gaps and leveraging robust policy frameworks, AVS can contribute to a more sustainable and resilient energy-agriculture nexus.

The findings are directly relevant to Malaysia's planning agenda, particularly the National Energy Transition Roadmap and Twelfth Malaysia Plan. Aligning agrivoltaics with existing solar schemes, land-use zoning, and rural electrification strategies can support balanced development and strengthen national food–energy security.”

This review is limited to peer reviewed English language publications, excluding grey literature and non-English sources. As systematic mapping emphasises breadth over depth, the review identifies patterns rather than performing meta-analytic comparisons. This review provides a foundation for future research, policy development, and investment strategies aimed at advancing the adoption and economic optimization of agrivoltaic systems.

ETHICAL CONSIDERATIONS

This study is based solely on published literature; no human subjects or primary data were involved. Ethical approval was not required

DECLARATION OF COMPETING 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.

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