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Agrivoltaics: a paradigm for sustainable dual land use - an overview

C.A. Arredondo[1,*], A.G. Arredondo[2], C.E. Arrieta Gonzalez[1], V. Rajamani[3] and S. Sarkar[4]

[1]Universidad de Medellín, Facultad de Ingenierías, Grupo de Investigación en Energía - GRINEN, Carrera 87 N°30 – 65, Medellín, Colombia
[2]Universidad de Medellín, Facultad de Ingenierías, Grupo de Investigación en Energía - GRINEN, Estudiante Ingeniería en Energía, Carrera 87 N°30 – 65, Medellín, Colombia
[3]Fachhochschule Dortmund, Mechanical Engineering, Sonnenstraße 96, DE44139, Dortmund, Germany
[4]RV College of Engineering, Department of Electrical and Electronics Engineering, Mysore Rd, RV Vidyaniketan, Post, Bengaluru, IN560059 Karnataka, India
[*]Correspondence: caarredondo@udemedellin.edu.co

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Abstract. Agrivoltaic systems is an emerging solution that combines agricultural production with photovoltaic energy generation on the same area. This paper synthesizes findings from approximately 251 peer-reviewed studies, technical reports, and real-world applications to explore the classification, benefits, and implementation of agrivoltaics systems globally. Case studies from Japan, France, Africa, and Latin America reveal yield increases above 10% for certain crops under partial shading and energy production outputs of up to 1.5 MW ha^{-1}, depending on the panel type and configuration. The overview also examines key technological developments, such as bifacial modules and smart irrigation, which improve efficiency and resource management. Additionally, it discusses the economic, environmental, and social benefits and identifies the main barriers to widespread adoption. By evaluating current challenges and future perspectives, this overview provides a comprehensive synthesis of how agrivoltaic systems contribute to sustainable energy and food production, highlighting their global relevance, integrating emerging technologies, and emphasizing the policy frameworks that support successful deployment.

Key words: agrivoltaics, dual land use, photovoltaic systems, sustainable agriculture, energy transition, climate resilience.

INTRODUCTION

In recent years, there has been a surge of interest in novel solutions at the nexus of climate change, renewable energy generation, and sustainable food production. Agrivoltaics has emerged as a key area of focus, representing an integrative solution that combines photovoltaic energy production with agricultural practices. This dual land-use strategy not only harnesses solar energy but also upholds the principles of sustainable agriculture by enhancing land efficiency and fostering ecological balance.

Agrivoltaic system offer a broad spectrum of benefits, including renewable energy generation, greenhouse gas emissions reductions, and contributions to rural economic growth in line with Green New Deal objectives (Proctor et al., 2021). Additionally, it provides solutions to land-use conflicts by enabling concurrent agricultural and photovoltaic utilization, thereby reducing competition for land resources (Tomich et al., 2011).

Unlike conventional photovoltaic installations, which often displace agricultural activities, agrivoltaics maintains agricultural productivity while contributing to renewable energy goals. This dual approach supports food-energy-water nexus objectives by creating favourable microclimatic conditions, conserving water, and fostering rural energy self-sufficiency.

Despite its initial slow adoption, agrivoltaics has recently gained significant traction globally, driven by increasing interest and advancements in research (Touil et al., 2021). The concept, also referred to as agrophotovoltaics, agrovoltaics, agrisolar, or dual-use solar, was first proposed by proposed by Adolf Goetzberger in Germany around 1982 (Goetzberger & Zastrow, 1982). Since then, it has evolved into an innovative strategy for sustainable energy and agricultural practices, offering a complementary solution that optimizes land use and transforms both the energy and agricultural sectors (Mamun et al., 2022; Wagner et al., 2023).

Agrivoltaic systems (AVS) combine photovoltaic (PV) energy generation with agricultural production on the same land, addressing both energy transition goals and agricultural productivity challenges (Dupraz et al., 2011), (Barron-Gafford et al., 2019). Initially conceptualized to optimize land use efficiency, the approach now encompasses diverse configurations, technological innovations, and integration models tailored to different crops, climates, and socio-economic contexts (Dinesh & Pearce, 2016; Weselek et al., 2019). By integrating agricultural productivity with renewable energy generation, agrivoltaic systems represent a versatile approach capable of addressing multiple sustainability challenges, from resource efficiency to climate adaptation, while aligning with broader policy and development objectives (van de Ven et al., 2021; Lu, 2024). These systems can also play a role in rural electrification and decentralized energy supply, as evidenced in related renewable energy initiatives (Dunmade, 2021), expanding their socio-economic relevance in both developed and developing regions.

Agriculture is a considerable energy-consuming sector, contributing significantly to global greenhouse gas emissions (Bumbiere et al., 2023). Implementing energy management strategies is therefore fundamental for achieving sustainability. Agrivoltaic systems offer an innovative solution to enhance energy efficiency while maintaining agricultural productivity, directly supporting global emission reduction and land optimization goals.

While several reviews have addressed the technical and environmental benefits of agrivoltaic systems, few have provided a comprehensive synthesis that captures their global applicability, long-term economic viability, and region-specific implementation dynamics. There is also limited discussion on social acceptance, policy integration, and infrastructure readiness (factors crucial for widespread adoption). This qualitative overview aims to fill those gaps and offer a broader understanding of how agrivoltaic systems connect with diverse agricultural and energy contexts.

This paper synthesizes key qualitative findings on agrivoltaics, exploring the classification, benefits, case studies, emerging technologies, and challenges. It is based on a structured literature review of 251 peer-reviewed articles and technical reports selected using clear inclusion criteria, as described in the Methodology section. By delving into the interdependencies of energy and agricultural production, also seeks to identify a path forward for agrivoltaics, underscoring its potential as a key component of sustainable development and a driving force for global change. The results are structured thematically to highlight key trends, case studies, benefits, and challenges in the implementation of agrivoltaics systems worldwide.

METHODOLOGY

This overview is based on a systematic synthesis of scientific literature designed to capture the global landscape of agrivoltaic systems. A multi-faceted methodological approach was used to examine the classification, implementation, benefits, and emerging technologies associated with agrivoltaics across various regions and agricultural contexts. The review integrates comprehensive literature analysis, global case studies, and selected experimental findings to evaluate the environmental, technical, and policy dimensions of agrivoltaic systems.

The methodological framework followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021), and involved a multi-stage process of literature identification, screening, and eligibility assessment.

The literature search was conducted across four academic databases: Scopus, Web of Science, Google Scholar, and MDPI, targeting publications between 2010 and 2024. In addition to the 251 studies included through the formal selection process, a small number of relevant 2025 publications, identified during the final manuscript revision stage, were cited to incorporate the most recent developments in the field. These publications were not part of the systematic pool and are therefore not reflected in the PRISMA counts. The search utilized a combination of keywords, including ‘agrivoltaic systems’, ‘solar energy in agriculture’, ‘dual land use’, and ‘sustainable agriculture’ to identify a broad spectrum of relevant studies. The initial search yielded an initial pool of 2087 records.

All retrieved records were compiled, and 396 duplicates were identified and removed, resulting in 1691 documents. These were screened by title and abstract screening based on predefined inclusion criteria: (1) the document must be a peer-reviewed journal article or a technical report from a recognized institution; (2) its primary focus must be the integration of solar energy and agriculture; and (3) it must directly discuss themes such as system performance, observed benefits, implementation challenges, or emerging technologies. Based on this screening, 1123 records were excluded as they did not meet the scope of our review.

The remaining 568 articles proceeded to a full-text evaluation to assess relevance and methodological transparency. Studies that lacked methodological transparency, provided no empirical insights, or did not substantively address agrivoltaic systems were excluded, resulting in a final selection of 251 publications. Additional documents from institutions such as NREL, NSEFI and Fraunhofer ISE were included to support case-specific discussions. Geographic diversity was also considered to reflect the wide adaptability of agrivoltaic systems.

The selected sources were thematically categorized to inform the structure of this overview. Case studies from diverse regions were analyzed to highlight technical performance, crop compatibility, and institutional frameworks. Recent developments in agrivoltaics technologies were reviewed to assess their effectiveness and practical applicability. This multidisciplinary and structured approach ensured a comprehensive assessment of the agrivoltaics landscape. The review process is summarized in the PRISMA flow diagram in Fig. 1.

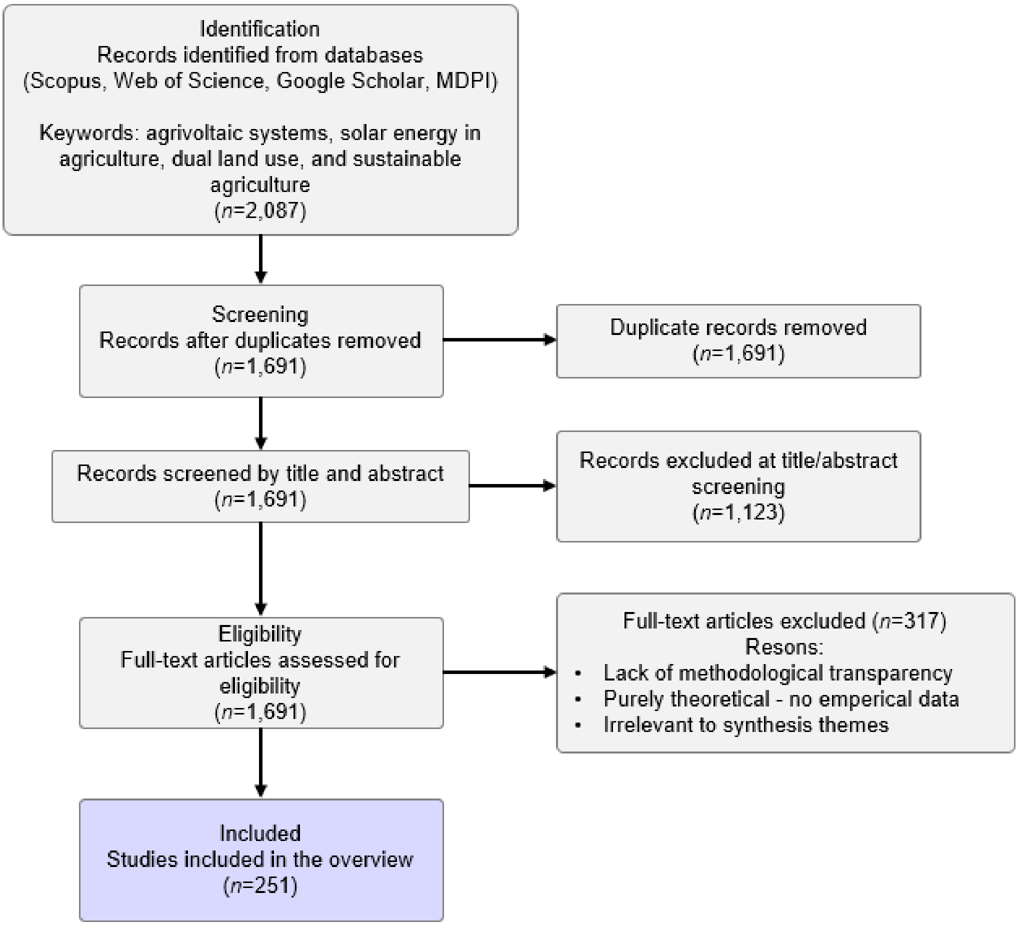

Figure 1. Overview of the research methodology applied in the agrivoltaic systems review. Source: Own elaboration.

The findings from this literature synthesis are presented in the subsequent sections, which details the key themes and insights identified through the methodological process described above.

CLASSIFICATION OF AGRIVOLTAICS

Agrivoltaic systems are classified according to several criteria in order to facilitate a deeper understanding of their implementation and to enable more effective optimization (SETO. 2022), (Sekiyama & Nagashima, 2019). Notable classifications include configuration type, application type, and system type. The National Renewable Energy Laboratory (NREL) provides a detailed explanation of the application type classification as follows (Macknick et al., 2022).

Classification by Configuration Type

Elevated Systems: Photovoltaic modules are positioned over crops at heights above 1.8 meters, protecting against severe weather and creating a controlled microenvironment. This setup benefits regions with high temperatures and intense sunlight but requires careful management to balance shading with sunlight needs for high-value crops like berries and grapes, optimizing energy production and crop yield.

Inter-row Systems: Vegetation is grown between rows of photovoltaic modules, allowing for larger farming equipment and extensive operations. Although these systems offer less direct weather protection and ensure sufficient sunlight for photosynthesis and growth. Typically, these systems are used for lower-value crops like grass, cereals, and hardy vegetables, which are resilient to light and environmental variations (Macknick et al., 2022).

Classification by Application Type

Crop and Food Production: The integration of agrivoltaics into crop production confers benefits regarding microclimate management. This is achieved through the provision of partial shade, which serves to reduce water evaporation, lower soil temperature, and protect plants from extreme heat. This enhances water efficiency and can increase crop yields, particularly in arid and semi-arid regions (Macknick et al., 2022).

Livestock Production: Integrating animals like sheep, cows, poultry, bees, and rabbits with solar panels offers significant benefits. Sheep manage vegetation by feeding, reducing maintenance needs. The shade provided by the panels can also reduce heat stress in animals, improving animal welfare and productivity (Macknick et al., 2022).

Ecosystems Services Provision: These systems are crucial for environmental conservation, enhancing biodiversity by creating habitats for pollinators and wildlife, enhancing biodiversity. Such a system enhances soil health through the deposition of organic matter and microbial activity, which are essential for sustainable agriculture. Furthermore, they facilitate the provision of clean water, climate regulation, and recreational opportunities, thereby linking renewable energy with environmental protection (Macknick et al., 2022).

Solar Greenhouses: This approach combines energy production with the creation of optimal agricultural environments. The integration of photovoltaic panels into greenhouses enables farmers to effectively manage light and temperature, thereby promoting optimal plant growth. This approach enables the year-round cultivation of high-value crops and reduces dependency on external energy sources (Macknick et al., 2022).

In Fig. 2, a classification of agrivoltaics systems according to their intended application is presented.

According to Fraunhofer Institute for Solar Energy Systems (ISE), agrivoltaics can also be classified by system type (Fraunhofer Institute for Solar Energy Systems ISE. 2022), as follows.

Classification by System Type

Open Systems: Including ground-level, interspace, and aerial / overhead modules (Fig. 2), are designed to adapt to a variety of agricultural practices (Fig. 3). Ground-level systems are well-suited for permanent grasslands and grazing animals, while interspace systems are ideal for use between crop rows. Aerial / overhead systems improve air circulation and environmental protection, with solar tracking enhancing energy capture and efficiency without disrupting existing farming practices.

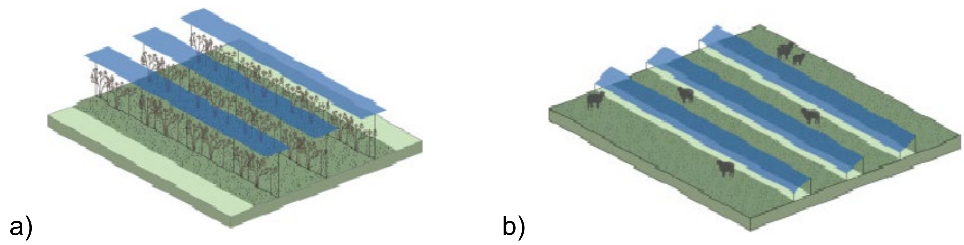

Figure 2. Types of open agrivoltaic systems: a) Overhead system with fixed modules, and b) Interspace system with fixed modules (Biró-Varga et al., 2024).

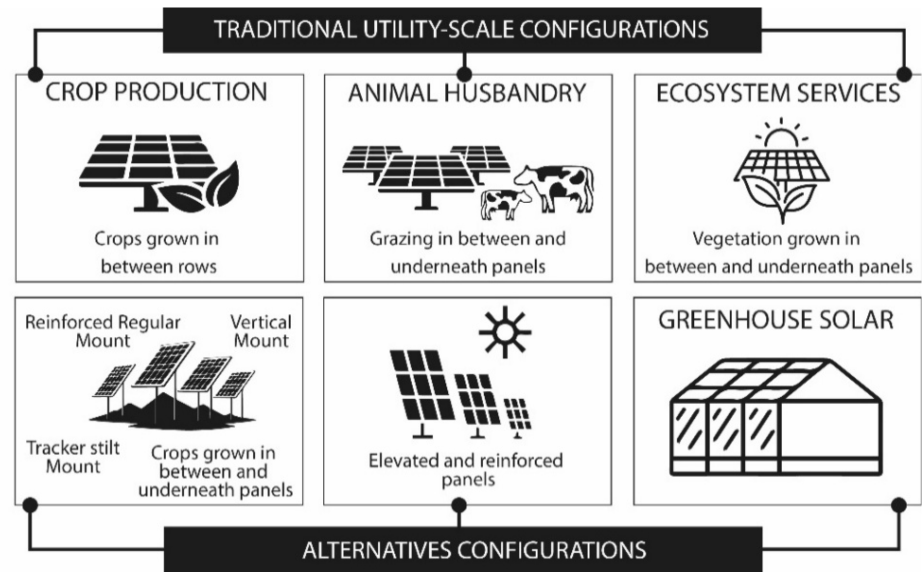

Figure 3. Classification of agrivoltaics systems by application. Adapted from (Dreves, 2022).

Closed Systems: Which can be photovoltaic greenhouses, combine solar panels with greenhouse technology to create controlled microclimates that enhance crop production. The aforementioned systems provide shading, thereby reduce the need for artificial cooling, and allow for the creation of specific growing conditions. The electricity generated is used to power greenhouse operations, making the system highly energy-efficient and sustainable (Dreves, 2022).

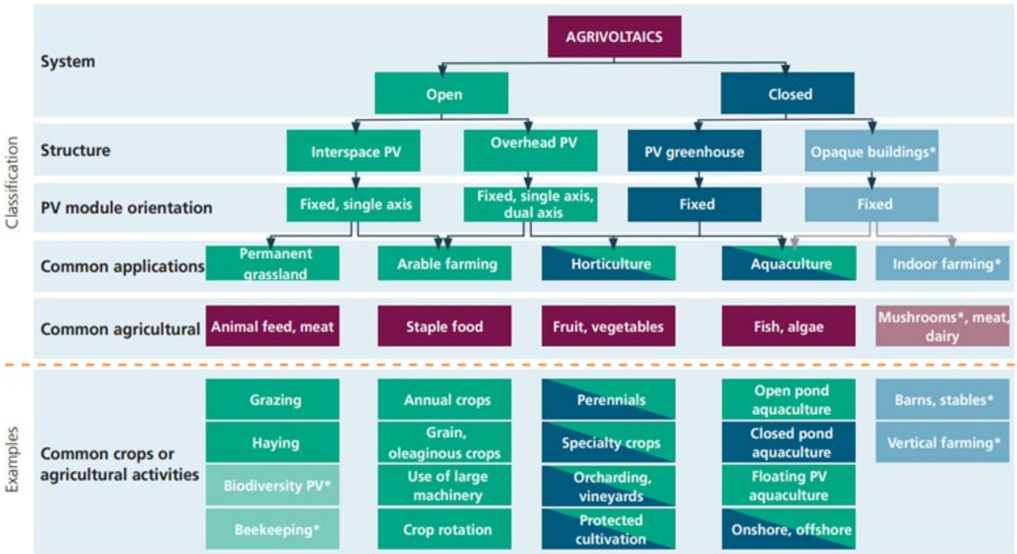

Figure 4. Classification by type of agrivoltaic system (Fraunhofer Institute for Solar Energy Systems ISE (2022)).

Fig. 4 illustrates the classification by type of agrivoltaic system. The classification system allows agrivoltaic systems to be adapted to a variety of agricultural and environmental contexts, enhancing efficiency and sustainability. By optimizing land use, agrivoltaics enhance crop and livestock productivity while improving the performance and benefits of photovoltaic systems (Dreves, 2022). This approach represents a transformative shift in sustainable agriculture and energy production.

BENEFITS OF AGRIVOLTAIC SYSTEMS

Agrivoltaic systems offer farmers a valuable opportunity to diversify their income streams. They facilitate the simultaneous production of electricity and crops, providing an additional revenue stream. This dual capability is especially valuable in rural areas with limited economic opportunities, as it provides a means of financial stability through the sale of both energy and agricultural products (Walston et al., 2022; PV Tech Power (2023); Wydra et al., 2023)). In the United States, several states have identified the potential of agrivoltaics and implemented financial incentives to encourage the development of these projects. For instance, the state of Massachusetts offers a tariff add-on of $0.06/kWh for agrivoltaic projects through its SMART program (Pascaris, 2021), while the state of New Jersey has authorized a pilot agrivoltaic program of up to 200 MW on non-preserved farmland, alongside funding a research system at Rutgers University (PV Tech Power (2023); Kirto et al., 2024)). Furthermore, Colorado has also invested in agrivoltaic research with the objective of optimizing its economic, technical, and environmental benefits (PV Tech Power (2023); Uchanski et al., 2023)). These initiatives highlight the significant economic potential of agrivoltaic systems for a broader adoption and for energy production (Pascaris et al., 2023).

While the benefits of agrivoltaic systems are substantial, it is important to recognize the potential trade-offs that may emerge during implementation. For instance, although agrivoltaics can generate additional income through energy production, the initial capital investment for elevated mounting structures are higher than for ground-mounted PV systems (Trommsdorff et al., 2022). Also, the use bifacial modules, or smart irrigation systems may offset short-term economic gains, particularly in small-scale or resource-constrained farms (see Case studies and emerging technologies sections for detailed analysis). The higher capital expenditure and the operation and maintenance costs need to be considered to determine costs. On the other hand, the sale of both electricity and agricultural products needs to be considered for the calculation of Return on Investment (ROI) (Sturchio & Knapp, 2023). Similarly, while crop yields may benefit from improved microclimatic conditions, not all plant species respond positively to partial shading, and site-specific adaptation is required to ensure long-term productivity. In some cases, land-use efficiency might also be affected if the solar infrastructure limits access for machinery or harvesting activities. These trade-offs do not negate the benefits of agrivoltaics but make clear the importance of tailored system designs, proper crop-panel matching, and supportive policy frameworks to maximize net benefits. A critical understanding of these limitations can enhance decision-making and promote the sustainable scaling of agrivoltaic practices.

From an environmental perspective, agrivoltaic systems provide numerous benefits that significantly contribute to sustainability and environmental conservation. The integration of solar panels with crops aids in soil conservation and improving water quality. Vegetation beneath the panels mitigates soil erosion and reduces water run-off (Walston et al., 2022; Wydra et al., 2023). This is of particular importance in areas prone to desertification and soil degradation (Dreves, 2022). Moreover, agrivoltaic systems can enhance the efficiency of solar panels by reducing the temperatures around them, which improves their performance and decreases water evaporation, thereby reducing the irrigation needs (Marrou et al., 2013; Dreves, 2022). Furthermore, these systems promote biodiversity by providing habitats for pollinators and other species. This biodiversity boost benefits local ecosystems and agricultural production by improving pollination services (Dreves, 2022), (The potential of agrivoltaics for the US). Overall, the environmental benefits demonstrate the potential of agrivoltaic systems to foster more sustainable and resilient agriculture, while simultaneously advancing renewable energy goals and reducing carbon emissions (Wagner et al., 2023). These benefits serve to illustrate the transformative impact on modern agricultural and environmental practices.

From a technical perspective, agrivoltaic systems offer significant benefits for photo-voltaic systems. The presence of crops beneath the solar panels provides a natural cooling effect, which is particularly advantageous in warm climates where high temperatures can reduce solar panel efficiency (Jerome et al., 2022). Studies have indicated that lowering the temperature around the panels enhances their performance and increases energy output (Sheik et al., 2022), (Kumari et al., 2022). In addition, the partial shading provided by the panels helps to retain soil moisture, thus reducing the need for frequent irrigation and conserving water resources (Omer et al., 2022).

The integration of vegetation with solar installations represents an effective means of controlling weed growth. This results in a reduction in the necessity for mechanical or chemical weed control methods, thereby lowering the maintenance costs associated with photovoltaic systems. Furthermore, the vegetation beneath the panels contributes to soil health by adding organic matter and promoting beneficial microbial activity (Jiufu et al., 2024). These factors not only enhance the technical viability of agrivoltaics systems but also support eco-friendly agricultural practices, thereby their sustainability (Time et al., 2024). These benefits illustrate how agrivoltaic systems can optimize the performance of solar panels, reduce operational costs, and enhance energy production.

While the benefits of agrivoltaic systems are widely acknowledged, distinguish between theoretical claims and those substantiated by empirical evidence remains crucial. For example, pilot projects in Japan and France have demonstrated concrete outcomes, such as increased farmer income, enhanced land-use efficiency, and improved energy output stability. Similarly, studies in Kenya confirm benefits in water conservation and energy access for off-grid farming. However, in regions like Brazil, most benefits remain conceptual, pending long-term implementation data. A table that summarizes these comparative outcomes by highlighting the location, main applications, technologies, challenges, and policy support for agrivoltaic systems can be found in the Case Studies section (Table 1). This serves as a useful guide for future scalability and adoption strategies.

CASE STUDIES OF AGRIVOLTAIC SYSTEMS

Agrivoltaic systems have been adopted in diverse geographical contexts, offering insights into their adaptability, socio-economic impact, and integration with local agricultural practices. Notable case studies include countries such as Japan, France, Africa, China, and others, where pilot projects have been implemented to study the impacts and advantages of agrivoltaics systems. The case studies included in this section have been selected based on several criteria, including geographical diversity, variety of crops and agricultural practices, scale of implementation, and the specific socio-economic and environmental challenges addressed by each project. While many case studies reveal common benefits, such as increased land-use efficiency and improved crop yields, each also demonstrates distinct strategies, challenges, and policy settings that inform context-specific and scalable deployment of agrivoltaic systems.

Japan has been a pioneer in the implementation of agrivoltaic systems since the introduction of its feed-in tariff scheme in 2012. This approach has significantly augmented the country's renewable energy supply, with a notable growth in renewable energy between 2012 and 2019. In the country, agrivoltaic systems have been employed with over 120 different crop species, including rice, tea, and blueberries. Re-search indicates that these systems can provide shade that benefits certain crops by reducing water stress and improving the local microclimate, thereby enhancing agricultural productivity (Gonocruz et al., 2021; Nakata & Ogata, 2023; Chalgynbayeva et al., 2024). A case study conducted at the agrivoltaic experimental farm operated by the CHO Institute of Technology in Ichihara City demonstrated the effectiveness of a photovoltaic system with a total output capacity of 4.5 kW. The system secured a feed-in tariff rate of 48 yen (approximately 0.44 USD) per kWh (Sekiyama & Nagashima, 2019). Another study suggests that agrivoltaic systems in Japan could generate approximately 284 million MWh per year, which is equivalent to approximately 29% of the country's total electricity demand (Gonocruz et al., 2021). These studies may position Japan as a leader in this field.

France exemplifies how the adoption of agrivoltaic systems constitutes a key element of the country's energy transition efforts. A case study in the Pyrénées-Atlantiques region underscores the critical role of social acceptance and effective governance in the implementation of these projects. Researchers found that the integration of energy production with agriculture on the same land requires active community participation and a clear political vision. This collaborative approach serves to mitigate conflicts between different land uses, thereby fostering a harmonious coexistence of food and energy production (Carrausse & Arnauld de Sartre, 2023; DW News (2024)). The Pyrénées-Atlantiques case study highlights that the success of agrivoltaic systems relies on engaging local stakeholders and the establishment of supportive governance frameworks. By addressing potential conflicts and promoting community involvement, agrivoltaic systems can effectively contribute to the goals of agricultural sustainability and renewable energy. This illustrates the potential of agrivoltaic systems to enhance agricultural productivity and energy genera-tion, in alignment with France's broader objecttives for sustainable development.

A study conducted in India examines the potential for the deployment of agrivoltaic systems on existing grape farms. The results indicate that this implementation on a national scale could generate over 16,000 GWh of electricity, potentially meeting the energy demands of more than 15 million people (Malu et al., 2017).

One such interesting project is Cochin International Airport Limited (CIAL) in Kerela, India. The world's first airport to operate entirely on solar power, had previously conducted an experiment with organic farming on one of its solar plant sites within the airport premises. This Airport features an impressive setup of eight solar plants within its premises with total capacity of solar plants in Feb. 2020 of 42 MWp. It was noted that the project yields an annual organic produce output of approximately 60–80 tons. Additionally, the airport has established strong market linkages, enabling direct sales of its agricultural products to regular consumers and passengers, thereby creating an additional revenue stream. The success of this initiative is largely attributed to interspace cultivation techniques. Over 20 variety of vegetables are grown under this project (National Solar Energy Federation of India (2023)).

Several agrivoltaic pilot programs are being conducted across Africa in collaboration with European research centers. In Algeria, the Watermed 4.0 project has shown promising encouraging outcomes, with a significant increase in the yield and size of potato crops cultivated under agrivoltaic installations in comparison to uncovered fields. Furthermore, projects involving agrivoltaic systems can assist in restoring the fertility of agricultural areas that have been adversely affected by progressive infertility due to climate change or land aridity. This is achieved through the use of solar technologies for irrigation and water management, thereby enhancing agricultural productivity, (Randle-Boggis et al., 2021; Macdonald et al., 2022; DW News (2024)).

A case study conducted in Hungary on apple production revealed the economic potential of agrivoltaic systems. The utilization of agrivoltaic technologies in intensive and super-intensive apple orchards not only enhanced fruit production but also facilitated the coverage of high fixed costs associated with the installation of these systems. The study concluded that agrivoltaic systems are economically viable and can enhance the competitiveness of farmers by efficiently utilizing space and implementing sustainable agricultural practices (Chalgynbayeva et al., 2022, 2024).

The integration of agrivoltaics has the potential to advance Canada towards net-zero power generation and greenhouse gas emissions (Jamil et al., 2023a). A case study demonstrated that the installation of racking structures on grape farms could enable the country to generate over 10 GW of renewable electricity (Jamil et al., 2023b). This substantial increase in sustainable energy production underscores the transformative potential of agrivoltaic systems to contribute to the nation’s energy and environmental goals.

The United States has several incentives and research programs that have promoted the implementation of agrivoltaic systems. A noteworthy example is Jack's Solar Garden in Colorado, which integrates solar energy generation with agricultural practices. This project has facilitated sheep grazing and the creation of habitats for pollinators, showcasing the multifunctional and sustainable benefits of agrivoltaic systems for both the local community and the environment (Dreves, 2022; PV Tech Power (2023)).

Germany has been a pioneer in the research and implementation of agrivoltaic systems. The Fraunhofer Institute for Solar Energy Systems (ISE) conducted a study on a 50 MWp project in Maharashtra, India, demonstrating economic viability with a competitive levelized cost of electricity (LCOE). This project highlighted the importance of institutional structures and international cooperation to maximize the benefits of agrivoltaic systems, underscoring their potential for large-scale applications (Wydra et al., 2023; Chalgynbayeva et al., 2024.

Italian agrivoltaic systems have been employed to address the decline in soil fertility resulting from climate change. A collaborative project with Green Cross International and the public research agency ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development) led to the construction of a five-megawatt photovoltaic plant in an agricultural region of Morocco. This initiative demonstrated that agrivoltaic systems can improve the local microclimate, boost agricultural productivity, and provide energy for irrigation and water desalination systems, benefiting local communities and mitigating the effects of climate change (Di Francia & Cupo, 2023; DW News (2024)).

South Korea's experience highlights the dual benefits of agrivoltaics, with improved agricultural yields and reduced environmental impact facilitated by supportive government policies. A study demonstrated that the implementation of these systems on agricultural lands can improve energy efficiency and agricultural productivity while reducing environmental impact. These projects in South Korea have been supported by government policies that promote renewable energy adoption and the integration of agrivoltaic technologies (Kim, M. et al., 2021; Kim, Y. et al., 2023; Chalgynbayeva et al., 2024).

China has been a pioneer in the integration of agriculture and photovoltaic energy through various agrivoltaic projects. A study conducted between 2007 and 2016 has evaluated the development levels and coordination between the photovoltaic industry and agriculture. The results proven significant improvements in land use efficiency and agricultural productivity. The projects in China have highlighted the im-portance of resource coordination and optimized agricultural practices in order to fully realize the benefits of agrivoltaic systems (Xiao et al., 2021; Hu, 2023; Chalgynbayeva et al., 2024).

Latin American research focuses on agrivoltaic systems with the objective of enhancing agricultural productivity and renewable energy generation. These projects showcase their potential of agrivoltaics systems to address environmental challenges, improve land use efficiency, and support local economies through sustainable practices.

Brazil demonstrates how agrivoltaics can address both energy generation and food security in semi-arid regions. The Ecolume Agrivoltaic System, for instance, has demonstrated the dual benefits of generating renewable energy and improving agricultural productivity. The integration of aquaponic systems beneath solar panels, this project not only increased solar power production through the cooling effect of plant transpiration but also enhanced crop yields and provided protein sources through fish farming. These initiatives underscore the potential of agrivoltaic systems to address both energy and food security in degraded or desertified areas (IDB Invest; Mongabay News (2022)).

In Chile, agrivoltaic projects are designed to optimize the efficiency of land use in regions that are experiencing water scarcity and high energy demands. These projects, which are supported by organizations such as IDB Invest of Inter-American Development Bank, combine goat farming with solar energy production. They demonstrate how agrivoltaic systems can enhance agricultural resilience and renewable energy generation. This approach not only optimizes land use but also supports local economies by integrating sustainable agricultural practices with energy production (IDB Invest). A study focused on a 100 kWp east-west vertical bifacial agrivoltaic facility in Chanco suggests potential benefits for energy production and water conservation. The results indicate that vertical agrivoltaic systems can reduce the water demand of irrigated crops by 1410 m^3/ha while simultaneously generating renewable energy (Bruhwyler et al., 2023).

Argentina is implementing agrivoltaic systems with the dual objective of supporting sustainable agriculture and renewable energy goals. Projects in regions such as Patagonia are being implemented with the goal of integrating solar panels with traditional farming practices. The objective is to improve land use efficiency and provide stable energy supplies for irrigation and other agricultural needs. These initiatives are part of broader efforts to promote sustainable development and reduce the carbon footprint of agricultural activities (IDB Invest).

The case studies collectively demonstrate the transformative potential of agrivoltaic systems in improving agricultural productivity, addressing environmental challenges, and advancing renewable energy objectives across diverse geographical contexts.

On the other hand, it can be said that an important number of countries are actively promoting agrivoltaic systems through a combination of fiscal incentives, regulatory frameworks, and supportive policies. France leads with a robust legal framework under the 2023 Act APER (loi relative à l'accélération de la production d'énergies renouvelables), which recognizes agrivoltaics as a key component of its national renewable energy strategy. The French government provides financial support through the 'Plan de Relance', offering subsidies and streamlined permitting processes to facilitate the adoption of agrivoltaics (Masons, 2024). Germany also provides support for agrivoltaics through the Renewable Energy Sources Act (EEG), which offers feed-in tariffs and low-interest loans through the KfW (Kreditanstalt für Wiederaufbau) Renewable Energy Program. This makes it easier for farmers to manage the costs associated with these systems. In Japan, the Ministry of Agriculture, Forestry, and Fisheries (MAFF) provides subsidies and tax deductions to encourage the integration of solar energy into agricultural practices, with a stable income guaranteed through the country's feed-in tariff system (MAFF Japan (2021)). In the United States, states like Massachusetts offer additional financial incentives through programs like the SMART initiative, thereby in-creasing the viability of agrivoltaics as a local farming option (Pascaris, 2021).

The case studies reviewed reveal a set of shared patterns that help explain the success of agrivoltaic systems across different regions. Countries such as France, Germany, and Japan have advanced more rapidly due to supportive policies, financial incentives, and clear regulatory guidelines. Technological innovations have also played a key role. In Japan, bifacial panels help optimize light distribution, while in Brazil, systems that combine solar panels with aquaponics have shown improved productivity and better use of land. Climate conditions shape outcomes as well. Projects in arid regions such as Algeria and Chile benefit from water savings and improved microclimates created by solar shading. In addition, local engagement has proven essential. In France and the United States, strong community participation and inclusive governance have contributed to long term project acceptance. These experiences suggest that successful implementation of agrivoltaic systems depends on a combination of context specific technologies, active local involvement, and well aligned policy frameworks.

Table 1. presents a comparative summary of the global agrivoltaic case studies discussed in this section.

Table 1. Comparative Agrivoltaics Case Studies by Country

Country/ Region	Main Application	Key Crops	Technology Used	Outcomes	Challenges	Policy Support
Japan	Maximizing land-use efficiency in mountainous and rural regions	Rice, leafy greens, fruit trees	Fixed-tilt and elevated PV systems	Enhanced income, stable energy generation	Crop compatibility, shading issues	Government subsidies and research funding
France	Enhancing vineyard productivity and energy generation	Grapes (vineyards)	Dynamic PV panels with tracking	Reduced drought stress, stable yields	Regulatory complexity	Agri-PV pilot programs and national strategy
Kenya	Improving rural electrification and water access	Vegetables and grains	Fixed-tilt PV systems with water pumps	Reduced water loss, better irrigation	Cost, limited technical capacity	NGO and donor-supported pilot projects
Germany	Integrating agrivoltaics in temperate climates	Potatoes, beets, vegetables	Bifacial modules, smart sensors	Yield preservation and sCO_2 reduction	Public resistance, zoning laws	EU support and national climate plans
China	Rehabilitating degraded land, boosting energy	Goji berries, corn	Bifacial modules on elevated structures	Increased land productivity	High installation cost	National dual-use land policy
USA	Research and demonstration for commercial farms	Lettuce, kale, pollinator plants	Adjustable-height PV panels	Improved biodiversity, extended growing season	Lack of standardization	DOE-funded projects and local initiatives
India	R&D, governmental supported projects and commercial projects	Vineyards, Vegetables (20+ varieties e.g Tomatoes, onions, etc.	Mix of approaches using mono facial and bifacial Fixed panels above crops	Water saving and energy security	Small land holdings, awareness	KUSUM scheme and renewable incentives
Brazil	Feasibility analysis and early-stage pilots	Coffee, pastures	Experimental PV arrays	Theoretical benefits identified	Lack of long-term data	Limited, mostly academic support
Africa (Regional)	Supporting food-energy-water nexus	Various regional crops	Simple PV systems, often fixed	Community-level access gains	Low technical capacity, funding gaps	NGO-led support, minimal policy integration

Source: Own elaboration from the reviewed case studies.

EMERGING TECHNOLOGIES IN AGRIVOLTAICS

One of the most significant innovations in agrivoltaic technology is the use of bifacial solar panels. These panels are capable of capturing sunlight from both sides, increasing their efficiency. The light reflected from the ground and plants can be absorbed by the underside of the panel, thereby increasing the total energy produced. Furthermore, these panels facilitate the management of light and shade over crops, optimizing the microclimate for plants (Nakata & Ogata, 2023; Chalgynbayeva et al., 2024).

The performance of bifacial modules in agrivoltaic applications reveal substantial variability depending on environmental and design parameters. Field studies conducted in diverse agricultural contexts demonstrate that energy yield improvements from 10% to 30% compared to monofacial systems (Badran & Dhimish, 2024; GrowingSolarMist, 2025) with bifaciality factors ranging from 70% to 95%, depending on the cell technology used (Katsikogiannis et al., 2022; Mohd Zaki, 2024). Surface characteristics beneath the panels play a critical role in determining rear-side irradiance gains. For example, grass-covered soils can add approximately 5.2% additional energy, sandy surfaces about 10.8%, and highly reflective white surfaces up to 21.9% (Guarino et al., 2025). Advanced heterojunction cell technologies further push bifaciality values toward 95% to 100%, offering enhanced benefits in elevated agrivoltaic configurations where modules are installed positioned above crop canopies (Buari & Kumari, K., 2023; Yakubu et al., 2024).

Economic analysis of bifacial agrivoltaic systems present a trade-off between higher upfront costs and improved long-term performance. While bifacial modules typically cost $0.05/W to $0.15/W more than monofacial ones, representing a higher capital cost of 10% to 15% (Mouhib et al., 2022; Almarshoud et al., 2024), comprehensive lifecycle assessments indicate LCOE reductions of 8% to 10% due to energy output (Hussain & Ghosh, 2024). Global optimization analyses suggest that bifacial systems achieve economic viability through careful design choices, such as ground coverage ratios between 0.3 and 0.5, and site-specific tilt angle adjustments (Zhong et al., 2023). The financial demand is further enhanced by the ability to generate higher energy output using the same mounting infrastructure, avoiding proportional increases in balance-of-system costs.

Design optimization for bifacial agrivoltaic systems introduces distinctive challenges not present in traditional PV installations. Ground coverage ratio must be carefully balanced to manage inter-row shading while maximizing albedo capture (Muñoz García et al., 2024). Additionally, agronomic compatibility requires elevated mounting, typically 1 to 2 meters above the crop canopy, to ensure adequate sunlight for photosynthesis and to enhance rear-side irradiance.

Albedo management is another distinctive operational consideration in bifacial agrivoltaic systems. Since, rear-side energy gain depends directly on ground reflectivity, effective system planning must consider seasonal crop cycles, vegetation maintenance, and the potential use of reflective ground covers. These factors interact dynamically over time and should be integrated into the system’s agronomic and energy performance strategies to maximize year-round efficiency.

The technical and economic advantages of bifacial solar panels outlined above have significant implications for agrivoltaic deployment worldwide, particularly in regions where agricultural productivity and renewable energy expansion are both national priorities. India exemplifies this convergence, where the government's ambitious solar energy targets and the country's substantial agricultural sector create ideal conditions for bifacial agrivoltaic adoption.

India's bifacial PV panel market reflects this growing potential, with projections indicating expansion at a CAGR of 13.60% during the forecast period from FY2025 to FY2032, increasing from USD 488.11 million in FY2024 to USD 1,353.78 million by FY2032. Recent technological developments further support this growth trajectory. In September 2024, Sharp announced the launch of a 450 W bifacial TOPCon solar module with an efficiency of 22.52%, certified under IEC61215 and IEC61730 standards. The panel features an operating temperature coefficient of -0.29% per °C and is designed for both solar farms and rooftop installations, with compact dimensions enabling space-efficient deployment (Markets & Data, 2024).

These market developments are being translated into practical applications through several commissioned pilot projects that demonstrate the real-world implementation of bifacial agrivoltaic systems. The following case studies illustrate how the theoretical advantages of bifacial technology are being realized in operational agrivoltaic installations across India (GIZ, 2024).

The Parbhani installation in Maharashtra's Marathwada region represents one of the most comprehensive bifacial agrivoltaic demonstrations to date. This 5-acre facility, with a capacity of 1.4 MW as part of a larger 50 MW solar project, was commissioned on November 12, 2022, through a collaborative effort between SunSeed APV, Kanoda Energy, and GIZ. The project's design incorporates four distinct APV configurations alongside a control farming area, enabling systematic comparison of different approaches to agrivoltaic implementation. The installation's most notable feature is a 6000 m^2 elevated structure housing a shade net system for trellised vegetables, which demonstrates the practical application of albedo management principles discussed earlier. This elevated configuration enhances rear-side irradiance capture while providing optimal growing conditions for crops including watermelon, capsicum, muskmelon, and spinach. Lower-elevation configurations at 1.25 m and 1.75 m heights offer alternative cost-effective approaches for different agricultural applications. The project's sophisticated water management system, incorporating drip irrigation and soil moisture sensors, exemplifies how panel shading can be leveraged to reduce water consumption while maintaining crop productivity (Mongabay, 2024). With extensive instrumentation, the farm supports R&D in agrivoltaics, informing future designs and crop strategies shown in Fig. 5.

Complementing these agricultural applications, the National Institute of Solar Energy (NISE) has pioneered a distinct approach through its vertically-installed bifacial PV panel pilot project in Haryana. This 5 kW experimental installation positions bifacial panels vertically with east-west orientation, addressing the challenge of energy generation balance throughout the day while maximizing agricultural land availability. This configuration represents an innovative solution to the space competition between solar installations and crop cultivation (National Solar Energy Federation of India (2023)).

Figure 5. Green capsicum at elevated section I at agrivoltaics plant near Parbhani, India (Mongabay. 2024).

The Nashik facility in Maharashtra further demonstrates the scalability of bifacial agrivoltaic systems. Initially developed as a 250 kWp installation on a one-acre plot owned by Sahyadri Farms, an FPO, the project's success led to expansion to 500 kWp capacity. The installation features an elevated structure at 4-meter height with bifacial panels positioned at 6-meter pitch intervals, allowing cultivation of high-value crops including grapes, oranges, raspberry, tomato, and strawberry beneath the solar canopy. This project, developed through collaboration between Sunseed APV, Kanoda Energy, and GIZ, exemplifies the economic viability potential discussed in the technical analysis above. (Rahman et al., 2023).

Despite these successful demonstrations, pilot project experiences have revealed several implementation challenges that must be addressed for broader adoption. The higher capital costs associated with bifacial panels, typically 10% to 15% above monofacial alternatives, require careful economic optimization to achieve favorable lifecycle cost outcomes. Design complexity increases significantly as engineers must balance solar irradiance requirements for energy generation with photosynthetic light needs for crop productivity, necessitating site-specific optimization approaches. Furthermore, the dual-technology nature of agrivoltaic systems demands enhanced technical expertise from operators, requiring training programs that bridge agricultural and photovoltaic knowledge domains. Regulatory frameworks remain underdeveloped, with policy guidelines needed to provide clear pathways for project approval, grid interconnection, and agricultural land use compliance. These challenges underscore the need for continued research and development efforts to optimize system designs and crop selection strategies specifically adapted to diverse Indian agricultural contexts (National Solar Energy Federation of India. 2023).

Another significant technological advancement is the use of solar trackers, which adjust the orientation of the solar panels to follow the sun's movement throughout the day. This technology optimizes solar light capture and can be integrated with agrivoltaic systems to ensure that crops receive the optimal amount of light and shade, enhancing both energy production and agricultural yield (Casares de la Torre et al., 2022; Di Francia & Cupo, 2023).

The study on the Even-lighting Agrivoltaic System (EAS) introduces innovative concepts and potential future developments for agrivoltaics. The EAS confers economic benefits upon farmers, by increasing their income, providing uniform illumination for crops, and boosting the daily irradiation received by crops by 47.38% compared to conventional agrivoltaic systems (Zheng et al., 2021).

Smart irrigation systems represent another emerging technology in agrivoltaic applications, offering quantifiable benefits in water conservation, energy efficiency, and crop productivity. These systems integrate IoT sensors, automated controllers, and real-time data analytics to optimize water delivery based on soil moisture content, weather conditions, and crop-specific requirements (Tajima & Iida, 2021). Recent studies demonstrate that sensor-controlled irrigation systems, when implemented under photovoltaic panel structures, can cut irrigation water requirements by 20 to 35% (Elamri et al., 2018; Mohammedi et al., 2023), while simultaneously increase crop water-productivity by up to approximately 90 kg m^{-3} (AL-agele et al., 2021). In water limited regions, these systems have shown the potential to recover the initial investment, estimated at less than €6,000 per hectare, within three to five growing seasons, (Champness et al., 2023; Di Francia & Cupo, 2023; Di Gennaro et al., 2024); Zidane et al., 2025).

The integration of smart irrigation with agrivoltaic systems lies in the complementary relationship between solar panel microclimate effects and precision water management. Agrivoltaic canopies reduce net solar radiation, canopy temperature and soil-evaporation, thereby lowering crop water demand. Smart irrigation systems enhance these effects by delivering water efficiently based on real time sensor data. Studies in dryland regions of Arizona report midday leaf-water potential 40% less negative, and thus lower stress, inside agrivoltaic plots than in full sun, even when irrigation is halved (Barron-Gafford et al., 2025). Furthermore, modeling work conducted in Montpellier on lettuce crops showed that combining panel tilt adjustment with soil moisture thresholds could achieve 20 to 30% seasonal water savings while maintaining yield losses at or below 10% (Elamri et al., 2018).

From an economic perspective, the integration of smart irrigation systems within agrivoltaic installations presents favorable cost-benefit profiles. Commercial Internet of Things platforms designed specifically for agrivoltaics report total hardware and installation costs below €6,000 for a two-hectare block. This includes soil moisture probes, LoRa gateway and solar powered pump upgrades (Di Gennaro et al., 2024), representing only 3 to 5% of the total system cost associated with elevated single-axis agrivoltaic configurations (Zidane et al., 2025). A multi-region cost–benefit analysis in Italy estimated that the additional capital expenditure for precision irrigation reduces the levelized cost of electricity by 1 to 2 €/MWh, primarily due to lower panel soiling and improved photovoltaic efficiency. While water conservation yields a net present benefit of €800 to 1,500 ha^{-1} yr^{-1}, achieving payback periods of 3 to 4 years for wheat and solar energy combination (Di Francia & Cupo, 2023). The overall economic feasibility is further enhanced through energy integration strategies. For example, smart pumps powered directly from the DC output of agrivoltaics system can operate without relying on the power grid. The pumps can be scheduled during periods of reduced energy dispatch, thereby increasing the site's internal energy use by around 12% percent in simulation studies (Al Mamun et al., 2025).

Furthermore, few deployments have implemented combined strategies that integrate panel-tilt schedules with irrigation schedules. The development of integrated optimization frameworks that use environmental sensors alongside photovoltaic tracking remains an area of active investigation (Elamri et al., 2018; Navarro-González et al., 2023). Successful implementation depends on site specific features such as soil type, crop selection, and climate conditions, all of which influence sensor placement and irrigation control. The scalability from demonstration projects to commercial agricultural operations requires progress in standardizing technologies and cost reduction strategies.

Figure 6. Fish Pond set-up underneath PV-modules in Bhaloji, Rajasthan, India (National Solar Energy Federation of India. 2023).

Future developments in smart irrigation for agrivoltaics applications include the use of machine learning models capable of forecasting irrigation needs. These models rely on historical data, weather predictions, and real-time plant monitoring to guide water application with greater precision (Saikai et al., 2023; Umutoni & Samadi, 2024). Policy frameworks that include water-pricing and environmental incentives programs that reward verified water savings, could help improve the financial returns and encourage wider implementation (Giannoccaro et al., 2022; (Mooney et al., 2022). These technological and policy advances are expected to further improve water use efficiency while maintaining the productive combination of farming and solar energy, positioning smart irrigation as a key element in the evolution of precision agriculture in photovoltaic environment. An innovative approach in agrivoltaic systems is the 'Fish Pond Agri-PV System' located in Bhaloji, Rajasthan, India shown in Fig. 6. This 30 kW solar power project is integrated with a fish pond with total site capacity of 1MW and is likely part of the Prime Minister's Kisan Urja Suraksha evam Utthaan Mahabhiyan (KUSUM) scheme, which supports farm-based solar power initiatives. The system involves installing solar panels over or around the fish pond, enabling simultaneous electricity generation and aquaculture operations. The system likely serves a dual function: harnessing solar energy for electricity generation while potentially boosting fish production in the pond beneath. Research indicates that the shading provided by solar panels can help regulate water temperature, creating favorable conditions for aquaculture. While agrivoltaic is still an emerging technology, its potential to address food and energy security challenges, particularly in water-stressed regions, is making it an increasingly attractive option for sustainable development (National Solar Energy Federation of India (2023)).

CHALLENGES AND MITIGATION STRATEGIES IN IMPLEMENTING AGRIVOLTAIC SYSTEMS

One of the primary obstacles to the implementation of agrivoltaic systems is the necessity of ensuring compatibility between crop types and solar panels. Not all crops exhibit the same response to the partial shading provided by solar panels. The selection of appropriate crops is crucial to achieve the optimal balance between food pro-duction and energy generation. It is therefore essential that ongoing research be conducted to identify the most optimal crop-panel combinations and configurations (Chalgynbayeva et al., 2024). To address these compatibility challenges, research institutions have developed systematic approaches based on the 'five C's' framework: (1) Climate, soil and environmental conditions, (2) Configurations, (3) Crop selection, (4) Compatibility and flexibility, (5) Collaboration and partnerships (Macknick et al., 2022). The InSPIRE project identified these five key factors that contribute to the success of agrivoltaics initiatives. It provides a standardized yet adaptable methodology for guiding both crop selection and system design. By applying this approach, farmers can make evidence-based decisions about optimal crop-panel combinations suitable for their specific agricultural and climatic conditions (Macknick et al., 2022; Soto-Gómez, 2024).

The initial installation costs of agrivoltaic systems can be prohibitive for many farmers. The necessity for additional infrastructure, such as elevated structures for panels and enhanced irrigation systems, can significantly increase project costs. This financial burden may act as a deterrent for farmers, particularly those in regions with limited financial resources, from adopting this technology (Tajima & Iida, 2021). For example, a study conducted in Germany indicates that the implementation costs of agrivoltaic systems can be considerably higher than those of conventional ground-mounted PV systems. The use of bifacial modules has been found to result in an average cost increase of €326 per kWp. The costs associated with mounting systems can vary considerably. Tilted and overhead agrivoltaic systems installed at heights exceeding four meters have been found to cost, on average, €372 per kWp, in comparison to a mean cost of just €76 per kWp for standard ground-mounted systems. The aforementioned costs can range from €240 to €500 per kWp, depending on the specific system configuration. Furthermore, the costs associated with site preparation and installation of agrivoltaic systems can range from €190 to €260 per kWp, which is considerably higher than the €60 to €100 per kWp typically associated with ground-mounted systems (Pascaris, 2021). However, recent technological developments have increasingly focused on cost reduction through modular agrivoltaic systems designed for incremental deployment and reduced upfront investment. Research demonstrates a modular design approach, where each unit is prefabricated independently and assembled using interlocking components and bolted connections, facilitating both construction and scalability (Toledo & Scognamiglio, 2021; Zhang et al., 2025). This approach enables farmers to begin with small-scale installations and gradually expand capacity as financial conditions improve, thereby reducing the barrier to entry without technical performance. Additionally, collaborative financing models, such as peer-to-peer lending schemes, have been shown to accelerate the adoption of renewable energy technologies. These mechanism offer alternative funding pathways that bypass conventional banking systems, making agrivoltaic adoption more accessible, especially in underserved or credit-constrained contexts (Zhang et al., 2025).

Moreover, regulations and policies can also act as impediments to the implementation of agrivoltaic systems. Land use regulations, including restrictions on the height and placement of solar panels, can limit the viability of these systems. Additionally, the absence of specific incentives for agrivoltaics can impede their large-scale adoption. It is essential that governments develop policies that actively support the integration of agrivoltaic systems into current agricultural and energy practices. Likewise, studies on renewable energy expansion (Karapidakis et al., 2023) underscore that the lack of robust grid infrastructure and energy storage solutions can lead to further complications in the integration of intermittent energy sources, including agrivoltaics, particularly in remote or isolated regions.

In addition to the economic and regulatory challenges associated with the implementation of agrivoltaics systems, the limited access to reliable electricity infrastructure in rural areas poses a significant barrier to the widespread implementation of such systems. In many developing regions, where electrification rates remain low, agrivoltaics could serve as a decentralized energy solution, offering both electricity and agricultural benefits. However, as highlighted in previous rural electrification studies (Dunmade, 2021), successful adoption requires significant investment in grid stability, storage solutions, and technical expertise. Without appropriate infrastructure and policy frameworks to support energy distribution, agrivoltaic projects may struggle to deliver their full benefits, particularly in areas where agricultural communities face economic and logistical constraints. To overcome rural infrastructure constrains and limited technical expertise, demonstration projects and community-based learning have proven to be effective strategies for transferring agrivoltaic technology. Studies highlight the importance of partnerships between governmental agencies, solar energy providers, and local farming communities to facilitate the successful implementation of these systems. Such collaborations provide the necessary resources and assistance (Dupraz et al., 2011; Fraunhofer Institute for Solar Energy Systems ISE (2022); Zeddies et al., 2025)).

Furthermore, the implementation of supportive policies and the provision of specific financial incentives for agrivoltaic projects can help offset high initial costs associated with such projects (Schindele et al., 2020; Wagner et al., 2024). Subsidy programs, feed-in tariffs, and tax credits can facilitate the accessibility of these systems to farmers (Pascaris et al., 2021; Jamil & Pearce, 2023). Financial incentives can play a pivotal role in promoting the adoption of agrivoltaic technologies and fostering their integration into sustainable agriculture.

Finally, fostering collaboration between the public and private sectors can facilitate the implementation of agrivoltaic systems. Partnerships between governmental entities, solar energy companies, and farmers can facilitate the development of successful agrivoltaic projects by providing the necessary resources and assistance. Pilot programs and demonstration projects can also serve to showcase the benefits of agrivoltaic technology on a large scale, encouraging broader adoption.

In summary, the findings from the case studies, emerging technologies, and challenges discussed in this paper provide comprehensive answers to the research questions. The global applicability and effectiveness of agrivoltaic systems are clearly demonstrated with regard to diverse geographical and socio-economic contexts. Technological innovations are playing a critical role in improving system efficiency, while the identified challenges emphasize the importance of supportive policies and collaborative efforts in overcoming barriers to implementation. Together, these findings contribute to a more accurate understanding of how agrivoltaic systems can be successfully integrated into sustainable agricultural and energy practices.

CONCLUSIONS

Agrivoltaic systems offer a promising solution for integrating renewable energy generation with agricultural production, providing economic, environmental, and technical benefits. Case studies from Japan, France, Africa, and Latin America demonstrate diverse applications and successful implementations. These systems improve agricultural productivity by creating favorable microclimates, optimizing light and water use, and supporting higher crop yields. For the purpose of scalability, the economic implications in terms of capital, and operation and maintenance costs, as well as the technology costs (for example, tracking) need to be understood. There is also the need for establishing standardised systems designs as well as the documentation of best practices to enable widespread application of agrivoltaics.

Technological advancements, including bifacial solar panels, solar trackers, and smart irrigation systems, have played a key role in enhancing the efficiency and effectiveness of agrivoltaic systems. These innovations enable better resource management, improve solar panel performance, and encourage the adoption of sustainable agricultural practices.

Despite these promising benefits, several challenges remain, including the compatibility of crops with solar panels, high initial installation costs, and regulatory barriers. To address these challenges, further research is required to identify the most effective crop-panel configurations to develop supportive policies and financial incentives. Public-private collaborations are crucial for ensuring the availability of the necessary resources and support for the successful project implementation. Additionally, fostering interdisciplinary cooperation among researchers, policymakers, agricultural experts, and energy sector stakeholders will be essential to drive innovation and develop solutions adaptable to different environmental and socio-economic scenarios.

In conclusion, the integration of agrivoltaic systems holds significant potential for advancing sustainable agriculture and driving the energy transition efforts. Technical advantages for solar photovoltaic systems in agrivoltaics include enhanced panel performance due to natural cooling from crop transpiration, decreased vegetation-related maintenance, and improved soil conditions through organic matter deposition. Tackling the existing challenges and capitalizing on these innovations is essential for agrivoltaic systems to meaningfully contribute to climate change mitigation, rural development, and long-term sustainability.

Based on these findings, this integrative qualitative overview contributes to the field by combining global case evidence, emerging technologies, and policy perspectives to provide a context-adapted and scalable roadmap for the implementation of agrivoltaic systems.

This qualitative overview provides a comprehensive synthesis of agrivoltaic systems to deepen the understanding of their relevance across diverse contexts. However, it also acknowledges certain limitations that need further investigation. These include variability in crop responses under different panel configurations or panel shading, economic modeling over extended timeframes, and the scalability of systems across differing geographical and policy environments. Additionally, social acceptance and land tenure dynamics complexities remain underexplored areas with implications for widespread adoption. To advance the field, future research should emphasize region-specific design optimization, crop-panel compatibility assessments, full-lifecycle environmental impact analyses, and adaptable policy frameworks. Policymakers are encouraged to implement incentive structures, revise zoning regulations, and support pilot projects to foster adoption. Industry actors should prioritize modular designs, cost-reduction strategies, and collaborative research. Integrating agrivoltaic development with broader sustainability agendas, including water management, biodiversity preservation, and rural resilience, will be crucial for maximizing their societal and environmental value.

In summary, this overview highlights the significant potential of agrivoltaic systems to improve land use efficiency, strengthen climate resilience and adaptation, and enhance food and energy security across diverse geographical and socio-economic contexts. Technological innovations, including bifacial solar panels, solar tracking mechanisms, and integrated smart irrigation have demonstrated their effectiveness in optimizing both energy generation and agricultural productivity. To ensure broader adoption and scalability, the presence of supportive policy frameworks remain essential. These include targeted investment incentives, adaptative regulatory mechanisms, and collaborative efforts across research institutions, industry stakeholders, and government entities. Collectively, these findings reinforce the relevance of agrivoltaics as a practical and adaptable solution that contributes meaningfully to the goals of sustainable development.

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