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Environmental Impacts of Agri-Photovoltaics Systems on Local Ecosystems

M. M. Mundu[1] | J. I. Sempewo[2] | G. B. Mahoro[3] | Vidya Sankarapandian[4] | Daniel Ejim Uti[5]

[1]Department of Electrical, Telecommunication and Computer Engineering, SEAS, Kampala International University, Kampala, Uganda | [2]Department of Civil and Environmental Engineering, College of Engineering, Design Art and Technology, Makerere University, Kampala, Uganda | [3]Department of Biological and Environmental Science, Kampala International University, Kampala, Uganda | [4]Department of Microbiology and Immunology, Kampala International University, Kampala, Uganda | [5]Department of Research and Publications, Kampala International University, Kampala, Uganda

Correspondence: M. M. Mundu (mundu.mustafa@kiu.ac.ug) | Daniel Ejim Uti (dan4uti@gmail.com; daniel.ejimuti@kiu.ac.ug)

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ABSTRACT

Agri-photovoltaic (Agri-PV) systems integrate agricultural production with solar energy generation on the same land, offering a promising response to the dual global challenges of food security and renewable energy expansion under increasing land constraints. This review critically synthesizes current scientific evidence on the environmental, agricultural, and socio-economic impacts of Agri-PV systems, with particular emphasis on their implications for local ecosystems and sustainable land use. Using a systematic review approach, we examine how different Agri-PV configurations influence soil health, water use efficiency, microclimate regulation, biodiversity, and crop productivity across diverse climatic and geographic contexts. The evidence indicates that well-designed Agri-PV systems can enhance soil moisture retention, moderate extreme temperatures, and improve water-use efficiency, thereby strengthening agricultural resilience, particularly in arid and semi-arid environments. However, outcomes are highly context-dependent, with potential trade-offs arising from excessive shading, altered hydrology, soil compaction during installation, and ecological disturbances if systems are poorly planned or managed. Case studies from Asia, Europe, and Africa demonstrate that participatory design, adaptive system configurations, and supportive governance frameworks are critical for balancing food production and energy generation objectives. The review further evaluates the contribution of Agri-PV systems to multiple United Nations Sustainable Development Goals, notably SDG 2 (Zero Hunger), SDG 7 (Affordable and Clean Energy), SDG 13 (Climate Action), and SDG 15 (Life on Land), highlighting both synergies and potential conflicts. Key mitigation and policy strategies are identified to safeguard long-term environmental integrity and promote equitable adoption. Overall, Agri-PV systems emerge as a viable component of integrated food–energy–land strategies, provided that deployment is guided by context-sensitive design, inclusive governance, and evidence-based policy frameworks.

1 | Introduction

1.1 | Overview of Agri-Photovoltaics

Agri-photovoltaics (Agri-PV), also referred to as agrivoltaics, represents an integrated land-use strategy that combines photovoltaic (PV) electricity generation with agricultural production on the same land area. The core objective of Agri-PV systems is to maximize land-use efficiency by enabling the simultaneous production of renewable energy and agricultural outputs, thereby reducing direct competition between food production and solar energy deployment (Dupraz et al. 2011; Amaducci et al. 2018; Fashina et al. 2018). As global demand for both food and clean energy continues to rise, Agri-PV has emerged as a promising response to land scarcity and sustainability challenges.

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Beyond land-use efficiency, Agri-PV systems contribute directly to multiple Sustainable Development Goals (SDGs). By supporting stable or improved crop yields under changing climatic conditions, these systems can enhance food security (SDG 2: Zero Hunger). Simultaneously, they expand access to renewable energy (SDG 7: Affordable and Clean Energy) and contribute to climate mitigation efforts by reducing greenhouse gas emissions (SDG 13: Climate Action) (Firoiu et al. 2019; Sachs et al. 2019; Dhyani et al. 2021; Muhamad et al. 2022; Calvin et al. 2023; Mundu et al. 2024). This multi-dimensional contribution positions agrivoltaics as a strategic solution at the food–energy–climate nexus.

Agrivoltaic systems have gained increasing scholarly and policy attention because they directly address two escalating global challenges: food security and clean energy expansion within a single land footprint. Evidence from multi-year field trials demonstrates that well-designed dual-use configurations can improve overall land productivity, often expressed through land equivalent ratios (LER >1.0), by concurrently generating electricity and sustaining or enhancing crop yields (Dupraz et al. 2011; Marrou et al. 2013; Wydra et al. 2023). These outcomes are particularly significant in regions experiencing land pressure, rapid population growth, and climate stress, where competition between agricultural production and energy infrastructure is intensifying. Framing agrivoltaics as a land-use optimisation strategy therefore underscores the importance of system design, crop selection, and management practices in determining net ecological and socio-economic benefits.

Agri-PV systems can be broadly categorized based on structural configuration and application context. Vertical systems involve PV panels mounted on elevated or vertically oriented structures, allowing crops to be cultivated underneath or between panel rows. Such configurations are especially advantageous in high-density or space-constrained environments (Ghazal et al. 2023). Horizontal systems, in contrast, consist of PV panels mounted on horizontal frames, enabling crops to grow beneath or between the panel arrays; these designs are more commonly implemented in rural and peri-urban settings where land availability is less restrictive (Patel et al. 2018). Technological advancements—including bifacial PV modules capable of capturing reflected radiation from both sides and solar tracking systems that dynamically optimize panel orientation—have further enhanced the performance and adaptability of Agri-PV installations (Amaducci et al. 2018; Wydra et al. 2023).

The practical integration of solar infrastructure and agricultural activity is illustrated in figures 1 and 2 (Bellehsen 2023). Figure 1 presents a ground-level perspective that emphasizes the spatial arrangement between PV structures and underlying crops, highlighting potential microclimatic benefits such as shading and temperature regulation. Figure 2 provides an aerial view of an Agri-PV installation, demonstrating how strategically positioned solar arrays enable concurrent energy production and farming activities across the same land area. Together, these visual representations underscore the dual-functionality and spatial efficiency that define Agri-PV systems.

Despite rapid growth in research outputs and pilot deployments, recent comprehensive evaluations indicate that important gaps remain in understanding long-term system performance, contextual variability, governance frameworks, and socio-economic sustainability. These unresolved issues reinforce the need for integrative, policy-relevant synthesis that moves beyond site-specific case studies (Lepley et al. 2025). Within this context, the present review aims to consolidate current evidence on Agri-PV systems, clarify design and performance trade-offs, and identify priority areas for future research and decision-making.



FIGURE 1 | Ground-level view of Agri-PV system showing solar panels above agricultural crops.

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FIGURE 2 | Aerial view of agri-photovoltaic system integrating solar panels and agricultural crops.

1.2 | Significance of the Review

The integration of Agri-PV systems into agricultural practices is gaining significant attention due to its potential to contribute to sustainable development goals. By combining energy production with crop cultivation, Agri-PV systems offer a way to reduce land competition, which is important in areas where land resources are limited (Hoffacker et al. 2017). Understanding the environmental impacts of these systems is essential to ensuring that they provide net benefits without causing unintended harm to local ecosystems (Ferreira et al. 2024). The significance of this review lies in its comprehensive assessment of the environmental impacts associated with Agri-PV systems. By evaluating the effects on soil health, water resources, biodiversity, and microclimates, the review aims to provide a detailed understanding of how these systems interact with local ecosystems (Elamri et al. 2018; Amaducci et al. 2018). This knowledge is fundamental for developing strategies to mitigate potential negative impacts and enhance the overall sustainability of Agri-PV technologies (Efremov et al. 2022).

1.3 | Objectives and Scope

Systematically, the primary objective of this review is to evaluate the environmental impacts of Agri-PV systems on local ecosystems. This includes a detailed examination of how these systems affect soil quality, water usage, biodiversity, and microclimate conditions. By synthesizing findings from various studies, the review seeks to identify both the benefits and drawbacks of Agri-PV systems, providing a balanced perspective on their ecological implications. Moreover, the scope of this review encompasses a wide range of studies and implementations of Agri-PV systems, both globally and regionally. It covers various types of Agri-PV technologies and their applications in different agricultural contexts. However, the review acknowledges certain limitations, including variability in study methodologies and geographic differences, which may influence the generalizability of the findings. Despite these limitations, the review aims to provide findings that can inform subsequent studies, policy-making, and practical implementation of Agri-PV systems.

2 | Background and Context

2.1 | Historical Development of Agri-PV Systems

The concept of integrating photovoltaic systems with agricultural activities emerged as a response to the growing need for sustainable energy solutions that do not compete with agricultural land use. The idea was first proposed in the early 1980s, but it gained significant traction in the 21st century as technological advancements in both agriculture and solar energy made it feasible to combine these two sectors effectively (Dupraz et al. 2011).

The initial stages of Agri-PV development focused on understanding how solar panels could be installed on agricultural lands without significantly hindering crop growth. Early experiments demonstrated that certain crops could thrive under solar panels, which provided partial shading and helped to reduce water evaporation, thus enhancing water use efficiency (Dupraz et al. 2011). This period saw the development of various Agri-PV configurations, including elevated structures and vertical installations designed to minimize land use conflicts (Weselek et al. 2019; Hernandez-Escobedo et al. 2022; Wydra et al. 2023). Notably, one of the important indicators in the evolution of Agri-PV was the development of bifacial solar panels, which can capture sunlight from both

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sides. This innovation significantly improved the efficiency of Agri-PV systems by increasing energy yield without requiring additional land (Wilson et al. 2020; Kopecek and Libal 2021; Cubukcu and Gumus 2020; Mundu et al. 2022). Another critical advancement was the implementation of solar tracking systems, which allow panels to follow the sun's movement, thereby maximizing solar energy capture throughout the day (Awasthi et al. 2020).

In recent years, research has also focused on optimizing the spatial arrangement of solar panels and crops. Studies have explored various planting patterns and panel orientations to find configurations that maximize both energy production and agricultural yield (Marrou et al. 2013; Wydra et al. 2023). These innovations have contributed to the growing interest in Agri-PV as a viable solution for sustainable land use.

2.2 | Current Applications and Adoption of Agri-PV at Global and Regional Levels

Agri-PV systems have been implemented in various regions worldwide, reflecting diverse agricultural and climatic conditions. In Germany, one of the pioneers in Agri-PV research and development, several large-scale projects have been established to study the impacts of Agri-PV on different crops and to optimize system designs (Weselek et al. 2019; Bhandari et al. 2021). For instance, the Agrophotovoltaik project in Heggelbach demonstrated that Agri-PV systems could produce significant amounts of electricity while supporting the growth of various crops, including potatoes and wheat (Weselek et al. 2019; Hernandez-Escobedo et al. 2022).

In Japan, the government has promoted Agri-PV as part of its renewable energy strategy. The 'Solar Sharing' initiative allows farmers to lease their land for solar panel installation while continuing agricultural activities. This approach has led to the widespread adoption of Agri-PV systems, particularly in regions with limited land resources (Sakai et al. 2021). Correspondingly, the adoption of Agri-PV systems has yielded numerous benefits across different settings. One of the primary advantages is the efficient use of land, allowing for the simultaneous production of food and renewable energy. This dual-use approach helps to alleviate land use conflicts and supports sustainable development goals (Peláez et al. 2020; Wydra et al. 2023).

Additionally, Agri-PV systems have been shown to improve crop resilience to climate change. The partial shading provided by solar panels can reduce heat stress on crops, leading to more stable yields in regions prone to extreme temperatures (Marrou et al. 2013; Wydra et al. 2023). Furthermore, the reduced evaporation under the panels enhances water use efficiency, which is particularly beneficial in arid and semi-arid regions (Dupraz et al. 2011; Wydra et al. 2023). Overall, the successful implementation of Agri-PV systems in various regions highlights their potential to contribute to sustainable agriculture and renewable energy production. As technology continues to advance and more data becomes available, Agri-PV systems are likely to play an increasingly important role in addressing global food and energy challenges.

2.3 | Influence of Agrivoltaic Design Types on Food–Energy Performance

Different agrivoltaic system configurations uniquely influence the balance between crop productivity and solar energy generation. Vertical systems (tall, narrow arrays) reduce horizontal shading and are advantageous where land footprints are narrow or where vertical crops (e.g., vines) are grown; however, their geometry can reduce total energy capture per unit area compared to optimally tilted arrays. Tracking systems (single- or dual-axis) improve solar capture by following the sun's path and can increase energy yield substantially, but require greater inter-row spacing and structural complexity that may increase shading and cost. Rooftop and greenhouse agrivoltaics decouple electricity generation from arable land and are excellent for built environments or protected cultivation; their impacts on crop microclimates depend on panel transparency and mounting height. Floating agrivoltaics (on reservoirs and ponds) offer evaporation reduction and synergies with aquaculture, but ecological impacts on aquatic systems and maintenance needs require careful evaluation. Each design creates trade-offs between maximising energy output (dense arrays, tracking) and maintaining or improving crop yields (elevated panels, wider spacing). Matching design choice to crop light-requirements, local climate, and socio-economic objectives is therefore essential for sustainable land use.

3 | Conceptual Framework

3.1 | Theoretical Models and Frameworks

Several models and frameworks from environmental science and agricultural research can be adapted to understand interactions within Agri-PV systems. One such framework is the Ecosystem Services Framework, which focuses on the benefits that ecosystems provide to human well-being, including provisioning, regulating, cultural, and supporting services (Garfin et al. 2013; Guswa et al. 2014; Nnamchi and Mundu 2022). Correspondingly, the Ecosystem Services Framework can be quantified by assessing the value of different ecosystem services provided by Agri-PV systems. To calculate the total ecosystem service value (TESV), Equation (1) is used.

$$\mathrm{TESV} = \sum_{i=1}^{n} S_i \times V_i \tag{1}$$

In this model, S_i represents the area or amount of the service i, such as the area of crops produced or the volume of water conserved. V_i denotes the economic value per unit of the service i, for example, the market price of crops or the value of water savings. The total number of different ecosystem services considered in the calculation is represented by n. This equation helps in comprehensively assessing the multiple benefits provided by Agri-PV systems by assigning a quantifiable value to each service and summing these values to determine the total ecosystem service value. The Ecosystem Services Framework can be applied to Agri-PV systems by categorizing the impacts into different types of ecosystem services. For example, Agri-PV systems can enhance provisioning services by producing both food and energy. They can also influence

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regulating services by affecting microclimates, soil health, and water use efficiency (Elamri et al. 2018; Amaducci et al. 2018). Cultural services may be impacted through changes in landscaping aesthetics and recreational opportunities. Supporting services, such as biodiversity and nutrient cycling, are also critical areas of focus (Hoffacker et al. 2017).

Another relevant model is the Sustainable Livelihoods Framework (SLF), which is commonly used to analyze the interactions between human livelihoods and environmental resources. The SLF emphasizes the importance of different forms of capital (natural, social, human, physical, and financial) and how these capitals are affected by various external factors, such as policies and institutions (Marulanda et al. 2020; Donohue and Biggs 2015; Nnamchi, Mundu, Nnamchi, et al. 2021; Nnamchi, Mundu, Ukagwu, and Oyagbola 2021). This framework is useful for examining how Agri-PV systems influence agricultural productivity, energy generation, and socio-economic outcomes. Equation (2) is used to quantify the overall livelihood outcome (L) in the SLF model.

$$L = f(\mathrm{NC}, \mathrm{SC}, \mathrm{HC}, \mathrm{PC}, \mathrm{FC}, E, P) \tag{2}$$

In this equation, L represents the overall livelihood outcome. The variables NC, SC, HC, PC, and FC denote the different types of capital: natural capital (e.g., land, water), social capital (e.g., networks, relationships), human capital (e.g., education, health), physical capital (e.g., infrastructure, tools), and financial capital (e.g., income, savings). The terms E and P represent external factors such as the economic environment and policies, respectively. This function highlights that livelihood outcomes are influenced by the interplay between these capitals and external factors. Additionally, the Sustainable Livelihoods Framework helps in understanding the broader socio-economic impacts of Agri-PV systems. By examining how Agri-PV influences different forms of capital, researchers can assess the overall sustainability and resilience of agricultural communities. For instance, Agri-PV can enhance financial capital through additional income from energy production, while potentially improving natural capital by promoting sustainable land use practices. However, it is essential to consider potential trade-offs and synergies among different forms of capital to ensure holistic sustainability.

Lastly, the Integrated Assessment Models (IAMs) are used to evaluate the broad environmental, economic, and social impacts of Agri-PV systems, incorporating various data inputs and scenario analyses (Clarke et al. 2014; Pindyck 2013). IAMs can help in understanding the long-term implications of Agri-PV adoption, including greenhouse gas emissions reductions, energy savings, and land-use changes (Rogelj et al. 2018). These models facilitate the assessment of policy interventions and technological innovations on the sustainability of Agri-PV systems, guiding decision-makers in developing effective strategies (Nordhaus 2017; Kriegler et al. 2012). By integrating biophysical, economic, and social variables, IAMs provide a comprehensive framework for evaluating the multi-dimensional impacts of Agri-PV systems (Tavoni et al. 2011; Clarke et al. 2014). IAMs typically involve a combination of several interconnected sub-models. The Energy Balance Equation is given by Equation (3).

$$E_{\mathrm{total}} = E_{\mathrm{agri}} + E_{\mathrm{PV}} - E_{\mathrm{losses}} \tag{3}$$

where E_{total} is the total energy output, E_{agri} is the energy output from agricultural activities, E_{PV} is the energy output from photovoltaic systems and E_{losses} is the energy losses due to inefficiencies and other factors. By balancing energy inputs and outputs, the energy balance equation highlights the potential for Agri-PV systems to optimize energy efficiency and sustainability. The economic output equation links inputs of labor, capital, and technology to GDP, reflecting economic productivity as in Equation (4).

$$\mathrm{GDP} = f(L, K, T) \tag{4}$$

where GDP is the Gross Domestic Product, L is the Labor input, K Capital input and T Technology level. The environmental impact equation aggregates various environmental effects as in Equation (5).

$$\mathrm{EI} = \sum \left(\mathrm{EI}_{\mathrm{soil}} + \mathrm{EI}_{\mathrm{water}} + \mathrm{EI}_{\mathrm{biodiversity}} + \mathrm{EI}_{\mathrm{microclimate}}\right) \tag{5}$$

where EI is the total environmental impact, $\mathrm{EI}_{\mathrm{soil}}$ is impact on soil health, $\mathrm{EI}_{\mathrm{water}}$ is the impact on water resources, $\mathrm{EI}_{\mathrm{biodiversity}}$ is the impact on biodiversity, $\mathrm{EI}_{\mathrm{microclimate}}$ is the impact on microclimates. The environmental impact equation reveals the significant influence of Agri-PV systems on soil health, water resources, biodiversity, and microclimates, emphasizing the need for comprehensive environmental management while the carbon emissions equation captures the net impact of Agri-PV systems on carbon emissions as in Equation (6).

$$C_{\mathrm{emissions}} = C_{\mathrm{agri}} + C_{\mathrm{PV}} - C_{\mathrm{sequestration}} \tag{6}$$

where: $C_{\mathrm{emissions}}$ is the total carbon emissions, C_{agri} is the carbon emissions from agricultural activities, C_{PV} is the carbon emissions from photovoltaic systems and $C_{\mathrm{sequestration}}$ is the carbon sequestration from enhanced land management practices. The carbon emissions equation demonstrates the potential of Agri-PV systems to mitigate climate change through reduced emissions and enhanced carbon sequestration.

Finally, the social welfare equation encapsulates the overall well-being, considering income, environmental quality, and health as in Equation (7).

$$\mathrm{SW} = U(Y, E, H) \tag{7}$$

where SW is the social welfare, U is the utility function, Y is the income, E is the environmental quality and H is the health outcomes. The social welfare equation integrates economic, environmental, and health considerations, showcasing the broader societal benefits of Agri-PV systems. Correspondingly, Equations (3–7) collectively form the backbone of an IAM, enabling the assessment of the trade-offs and synergies between economic, environmental, and social outcomes in Agri-PV systems. Additionally, they provide a robust framework for assessing and optimizing the sustainability and resilience of Agri-PV systems, guiding policy and management decisions towards achieving sustainable agricultural and energy goals.

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3.2 | Integration of Agri-PV in Ecosystems

3.2.1 | Integrated Conceptual Framing

Understanding agrivoltaic systems requires a multi-framework perspective capable of capturing interactions across environmental, social, and energy dimensions. In this regard, an integrated framework drawing on the Ecosystem Services Framework and the Sustainable Livelihoods Framework (SLF) provides a robust basis for analysing Agri-PV systems. The Ecosystem Services framework explains how soil regulation, water conservation, climate moderation, and habitat provision translate into agricultural and ecological benefits, while the SLF highlights how agrivoltaics influences farmers' livelihood assets including natural, financial, physical, human, and social capital through improved crop stability, diversified income from electricity generation, and reduced climate risks (Mishra et al. 2021; Nnamchi, Mundu, Nnamchi, et al. 2021; Nnamchi, Mundu, Ukagwu, and Oyagbola 2021; Semeraro et al. 2023).

At a broader systems level, Integrated Assessment Models (IAMs) complement these frameworks by linking agrivoltaics to food–energy–water planning, land-use transitions, and long-term sustainability pathways. Together, these perspectives offer a coherent structure for interpreting trade-offs and synergies between food production, energy generation, ecosystem integrity, and rural socio-economic outcomes. This integrated framing is particularly important given the non-linear interactions that characterize agrivoltaic systems, reinforcing the need for holistic food–energy systems analysis (Foran et al. 2014).

3.2.2 | Biophysical and Human System Interactions

Within this integrated framework, Agri-PV systems are understood as dynamic socio-ecological systems composed of biophysical environments, human systems, and feedbacks between them. The biophysical environment includes soil health, water resources, biodiversity, and microclimatic conditions, all of which are directly influenced by the presence and configuration of photovoltaic infrastructure. Human systems encompass agricultural productivity, energy generation, economic returns, and social outcomes, which collectively shape livelihoods and local development trajectories (Mishra et al. 2021; Nnamchi, Mundu, Nnamchi, et al. 2021; Nnamchi, Mundu, Ukagwu, and Oyagbola 2021; Semeraro et al. 2023).

Changes in one system component can propagate through others. For example, microclimatic modifications induced by panel shading can affect crop growth and water demand, thereby influencing agricultural productivity and farm income. In parallel, revenues from electricity generation can improve household livelihoods and social well-being, creating reinforcing feedback loops that enhance overall system sustainability (Dupraz et al. 2011; Hoffacker et al. 2017).

3.2.3 | Other Key Variables and Quantitative Indicators

Several key variables underpin the assessment of Agri-PV–ecosystem interactions, including solar radiation and energy production, soil health, water use efficiency, biodiversity, and economic and social impacts. Evaluating how different Agri-PV configurations influence solar energy capture, microclimates, and crop performance is central to understanding system outcomes (Elamri et al. 2018; Nnamchi et al. 2020). Solar energy output is quantified using Equation (8):

$$E = A \times G \times \eta \tag{8}$$

where E is the energy yield (kWh), A is the area of the PV panels (m^2), G is the solar irradiance (kWh/m^2), and η is the efficiency of the PV panels.

Soil health is assessed through changes in moisture content, nutrient availability, and microbial activity, while water use efficiency reflects the influence of partial shading on evapotranspiration and irrigation demand. Water use efficiency is expressed using Equation (9):

$$\mathrm{WUE} = \frac{Y}{\mathrm{ET}} \tag{9}$$

where Y is the crop yield (kg / ha) and ET is the evapotranspiration (mm).

Biodiversity impacts associated with Agri-PV deployment—such as changes in plant and animal species composition—are commonly evaluated using diversity indices, including the Shannon diversity index shown in Equation (10):

$$H' = -\sum_{i=1}^{s} p_i \ln p_i \tag{10}$$

where H' is the Shannon diversity index, S is the total number of species, and p_i is the proportion of individuals belonging to species i.

Economic and social outcomes, including system viability and livelihood effects, are examined through cost–benefit analyses and social acceptance studies. Economic viability is often assessed using the net present value (NPV), defined in Equation (11):

$$\mathrm{NPV} = \sum_{t=0}^{T} \frac{R_t - C_t}{(1+r)^t} \tag{11}$$

where NPV is the net present value, R_t is the revenue at time t, C_t is the cost at time t, r is the discount rate, and T is the time horizon.

3.2.4 | System Dynamics and Feedback Analysis

Understanding the interdependencies among these variables is critical for developing sustainable Agri-PV systems that balance energy production with environmental and socio-economic objectives. Improvements in water use efficiency, for instance, may enhance crop yields and economic returns, but these gains must be evaluated alongside potential trade-offs affecting biodiversity or soil health.

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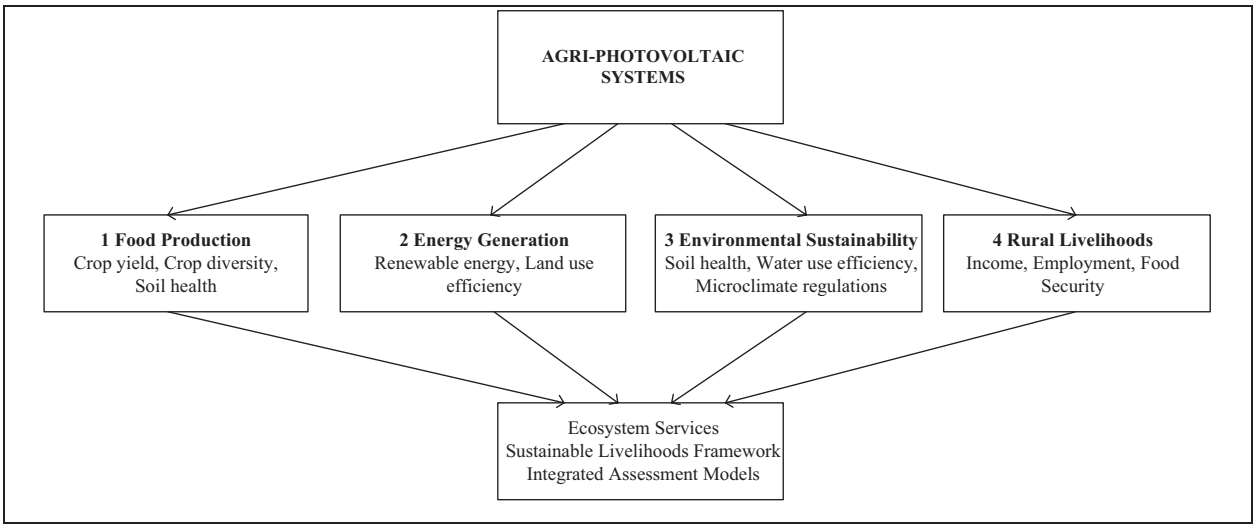


FIGURE 3 | Conceptual framework of ecosystem, livelihood, and energy interactions in agrivoltaics.

Equations (8–11) can be integrated into a comprehensive system-level model and solved iteratively using system dynamics tools such as STELLA, Vensim, or AnyLogic. Such simulations enable exploration of how changes in one component such as increased solar irradiance or altered panel spacing cascade through biophysical and human subsystems over time, providing insights into the resilience and long-term sustainability of Agri-PV systems.

Moreover, Figure 3. illustrates the interconnected relationships between agrivoltaic systems, food production, energy generation, environmental sustainability, and rural livelihoods, structured through the Ecosystem Services, Sustainable Livelihoods, and Integrated Assessment Models frameworks.

The framework demonstrates how improved soil health, water-use efficiency, and moderated microclimates support ecosystem services that enhance crop resilience, while energy generation diversifies income and strengthens rural well-being. Through the combined lenses of Ecosystem Services, Sustainable Livelihoods, and Integrated Assessment Models, agrivoltaics are presented as an integrated system that balances food–energy provisioning with ecological and socioeconomic outcomes.

4 | Methodology

4.1 | Review Design and Reporting Framework

This review adopted a rigorous and transparent systematic literature review design guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 framework. The methodological approach was selected to ensure reproducibility, minimize selection bias, and support robust synthesis across the interdisciplinary domains of agrivoltaics, agriculture, environmental science, engineering, and renewable energy. The overall strategy aligns with contemporary best practices in large-scale evidence synthesis and scientometric evaluation (Nedungadi et al. 2025).

4.2 | Data Sources and Search Strategy

To ensure comprehensive coverage of the agrivoltaics literature, three major academic databases were systematically searched: Scopus, Web of Science Core Collection, and Google Scholar. These databases were selected to capture both high-impact peer-reviewed studies and interdisciplinary research spanning technical, environmental, and socio-economic dimensions. Searches were conducted for publications between January 2010 and June 2024, encompassing early foundational work as well as recent advances in system design, crop–energy optimization, and sustainability assessment.

Keyword combinations were designed to capture both agricultural and energy-related dimensions of Agri-PV systems. The primary Boolean search string applied across databases was: (“agrivoltaic” OR “agrovoltaic*” OR “solar sharing” OR “agrisolar”) AND (“crop yield” OR “agricultur*” OR “food production” OR “soil” OR “microclimate”) AND (“solar energy” OR “PV system” OR “photovoltaic” OR “renewable energy” OR “energy yield”). Additional terms including “land-use efficiency”, “LER”, “dual-use”, “sustainability”, “environmental impacts”, and “design types” were incorporated during secondary refinement to ensure inclusion of studies addressing either food productivity, energy performance, or integrated food–energy outcomes.

4.3 | Eligibility Criteria

Studies were included if they met the following criteria: (1) peer-reviewed empirical or modeling-based investigations of agrivoltaic systems; (2) reporting at least one agricultural outcome (e.g., crop yield, microclimate modification, soil or water metrics) and/or one energy outcome (e.g., electricity generation, PV efficiency); (3) provision of system design specifications enabling comparison across vertical, horizontal, rooftop, floating, tracking, or greenhouse-integrated configurations; and (4) English-language publications within the 2010–2024 period.

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Similarly, exclusion criteria comprised: (1) studies lacking primary data or presenting purely conceptual commentary without measurable outcomes; (2) investigations focused on conventional photovoltaic installations without agricultural co-use; (3) publications with insufficient methodological detail to extract food–energy indicators; and (4) duplicate or non-peer-reviewed sources, except where government datasets provided verifiable quantitative parameters.

4.4 | Screening, Quality Assessment, and Data Extraction

The initial database search yielded 400 records related to the environmental and ecosystem impacts of Agri-PV systems. Following title and abstract screening, 300 articles were retained for further evaluation. Full-text assessment of 200 articles, based on the predefined inclusion and exclusion criteria, resulted in the exclusion of 100 studies. A standardized data extraction form was then applied to the remaining articles to collect information on authorship, publication year, geographic location, agrivoltaic system type and scale, environmental indicators assessed, methodological approaches, and key findings.

Moreover, quality assessment was conducted using criteria related to study design robustness, sample size adequacy, data collection methods, statistical rigor, and peer-review status. This process classified 66 articles as high quality, 30 as moderate quality, and 10 as low quality, ensuring transparency in evidentiary weighting and synthesis credibility.

4.5 | Quantitative Representation of the Review Process

To formalize the systematic review workflow and enhance transparency, a decision-based quantitative model grounded in basic set theory and probability was used to represent each screening and selection stage. Equation (12) defines the total number of articles initially retrieved from the databases:

$$A = \text{Total number of articles retrieved from databases} \tag{12}$$

Correspondingly, Equation (13) shows the process of screening the titles and abstracts of the retrieved articles. The total number of articles (A) is divided into relevant articles (R) and those excluded (E_1) based on their relevance to the study of Agri-PV systems and their environmental impacts.

$$A = R + E_1 \tag{13}$$

where R is the number of relevant articles after screening and E_1 is the number of articles excluded in the screening stage.

Furthermore, for the full-text assessment, it is represented by Equation (14). This equation describes the next stage where the full texts of the initially relevant articles are assessed in detail. The number of relevant articles (R) is divided into those that are reviewed in full (F) and those excluded after this detailed assessment (E_2).

$$R = F + E_2 \tag{14}$$

where F is the number of full-text articles reviewed and E_2 is the number of articles excluded after full-text assessment. Additionally, for the quality assessment of the full-text articles, each article is categorized based on its quality (high, moderate, or low) and some articles are excluded at this stage (E_3) if they do not meet the necessary quality criteria. This is represented by Equation (15)

$$F = Q_H + Q_M + Q_L + E_3 \tag{15}$$

where Q_H is the number of high-quality articles, Q_M is the number of moderate-quality articles, Q_L is the number of low-quality articles and E_3 is the number of articles excluded in quality assessment.

Equation (16) shows the articles that pass the quality assessment and from which relevant data is extracted. Where D is the number of articles from which data is extracted. It includes articles of high, moderate, and low quality.

$$D = Q_H + Q_M + Q_L \tag{16}$$

This final Equation (17) represents the synthesis of data extracted from the articles. Some articles were summarized qualitatively (S_Q) to identify key themes and patterns, while others were included in quantitative meta-analyses (S_M) to combine results and draw more robust conclusions.

$$D = S_Q + S_M \tag{17}$$

These Equations (12–17) help to systematically organize and quantify each step of the literature review process, ensuring a thorough and rigorous assessment of the environmental impacts of Agri-PV systems on local ecosystems.

4.6 | Contextual Stratification and Comparative Coding

To ensure robustness across diverse environmental and socioeconomic settings, all included studies were coded according to climatic zone (temperate, arid, semi-arid, tropical), geographic region, crop type (e.g., cereals, horticultural crops, forage, perennial systems), agrivoltaic design (fixed elevated, tracking, vertical, greenhouse-integrated, floating), and farming context (smallholder versus commercial systems). This stratification enabled systematic comparison of food and energy outcomes across heterogeneous conditions and reduced the risk of overgeneralization from geographically or climatically narrow case studies. Evidence from SDG-focused research in vulnerable and underrepresented regions further highlights the importance of context-sensitive agrivoltaic deployment strategies (Raman et al. 2024).

4.7 | Empirical Validation of SDG Outcomes

To substantiate claims related to Sustainable Development Goal (SDG) contributions, only studies reporting measurable and verifiable indicators such as crop yield variation, electricity

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generation capacity or output, income changes, water-use efficiency, or greenhouse gas mitigation were included in the SDG outcome synthesis. Conceptual discussions lacking empirical validation were excluded from this stage. This evidence-based validation approach ensures that reported SDG linkages are grounded in observed or quantifiable outcomes rather than inferred associations, thereby strengthening the credibility and policy relevance of the review findings.

5 | Environmental Impacts on Local Ecosystems

5.1 | Ecosystem Service Framing of Environmental Impacts

Environmental responses observed under agrivoltaic installations—including soil moisture retention, moderated microclimates, and reduced evapotranspiration—extend beyond isolated biophysical effects and constitute critical ecosystem services that underpin agricultural productivity and resilience. By mitigating temperature extremes, conserving soil organic matter, stabilizing soil structure, and improving water-use efficiency, agrivoltaic systems contribute directly to regulating and supporting ecosystem services essential for sustainable food systems. This ecosystem service perspective aligns agrivoltaic outcomes with broader sustainability objectives, including long-term soil fertility, water conservation, and climate-adaptive crop production.

5.2 | Impact on Soil Health

Soil responses under agrivoltaic systems are closely linked to regulating ecosystem services that support crop productivity and long-term land resilience. Panel-induced shading can moderate soil temperature fluctuations, reduce evaporation rates, and enhance moisture retention, thereby promoting soil biological activity and nutrient cycling. When appropriately designed and managed, agrivoltaic installations can also preserve soil structure and organic matter, strengthening the resilience of agricultural systems.

Empirical studies demonstrate that shading from PV panels reduces soil temperature variability and conserves soil moisture, particularly in regions with high solar irradiance (Amaducci et al. 2018; Dupraz et al. 2011). These conditions can improve soil fertility and reduce erosion risk. However, improper installation and maintenance practices may introduce negative impacts. For example, Marrou et al. (2013) reported that heavy machinery used during construction can compact soils, reducing porosity, aeration, and root penetration, thereby constraining crop performance.

5.2.1 | Soil Compaction and Mitigation Measures

Soil compaction represents one of the principal risks associated with agrivoltaic deployment. Construction activities and repeated vehicular movement beneath PV arrays can degrade soil physical properties if unmanaged. Effective mitigation strategies include restricting heavy machinery access, employing low-ground-pressure equipment, maintaining permanent vegetative cover, and applying controlled traffic farming practices. When such measures are implemented, agrivoltaic systems can preserve or even enhance soil structure over time.

5.3 | Impact on Water Resources

Agrivoltaic systems can significantly enhance water-use efficiency by reducing soil evaporation and crop water stress through partial shading. Research indicates that crops grown under Agri-PV systems often require less irrigation compared to those cultivated in open-field conditions (Weselek et al. 2019). Shading effects also modify microclimatic conditions around crops, influencing transpiration rates and overall water-use efficiency (Adeh et al. 2019).

These hydrological benefits represent an important regulating ecosystem service, particularly in semi-arid and drought-prone regions. Reduced evapotranspiration and improved soil moisture retention can extend irrigation intervals, buffer crops against heat stress, and reduce pressure on groundwater resources. Consequently, agrivoltaic deployment supports sustainable water management and contributes directly to SDG 6 (Clean Water and Sanitation).

However, potential negative impacts on local hydrology must also be considered. Concentrated runoff from panel surfaces can increase erosion and sediment transport, potentially affecting nearby water bodies and water quality if unmanaged (Barron-Gafford et al. 2019).

5.3.1 | Runoff, Erosion, and Hydrological Management

Design-based mitigation strategies are critical to minimizing adverse hydrological effects. Elevated mounting structures, staggered panel layouts, contour-aligned installations, vegetated swales, and designated infiltration zones can redistribute rainfall, enhance groundwater recharge, and reduce erosion risks. Such measures enable agrivoltaic systems to deliver net-positive hydrological outcomes while maintaining energy performance.

5.4 | Impact on Biodiversity

Agri-PV systems can alter habitat structure and resource availability, thereby influencing local biodiversity. Shaded microhabitats created beneath PV arrays may support plant species adapted to lower light conditions and provide shelter for various fauna. Adeh et al. (2019) observed that such shaded environments can enhance plant diversity by enabling the coexistence of shade-tolerant species.

Conversely, changes in land use and habitat configuration can disrupt existing ecosystems if agrivoltaic installations are poorly planned. Armstrong et al. (2014) highlighted that while some species benefit from newly created habitats, others may be displaced, leading to shifts in ecosystem composition and function. When appropriately designed and managed, however, agrivoltaic systems can contribute to biodiversity conservation and support SDG 15 (Life on Land).

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5.5 | Impact on Microclimates

Agrivoltaic installations modify local microclimates by influencing temperature, humidity, and airflow. The shading provided by PV panels can lower soil and air temperatures, reducing heat stress and creating more favorable growing conditions for crops. Hassanpour Adeh et al. (2018) documented significant reductions in soil and near-canopy air temperatures under Agri-PV systems, contributing to improved crop performance.

Microclimate moderation including reduced midday canopy temperatures, improved humidity profiles, and lower thermal stress—functions as a supporting ecosystem service that stabilizes plant physiological processes. These moderated conditions can enhance photosynthetic efficiency, reduce vulnerability during extreme heat events, and contribute to more stable yields. By fostering microclimatic resilience, agrivoltaic systems support climate-adaptive agriculture and contribute to SDG 13 (Climate Action). Nevertheless, altered microclimates may also introduce risks, such as increased frost incidence in cooler regions or changes in local precipitation patterns.

5.5.1 | Crop-Specific Shading Effects and Adaptation

While shading can reduce heat and water stress, excessive light reduction may negatively affect light-demanding crops. Adaptive strategies including optimized panel spacing, adjustable tilt angles, seasonal tracking, and crop selection based on shade tolerance—are therefore essential. These approaches allow optimization of agricultural productivity while maintaining energy generation targets.

5.6 | Ecological Disturbance and Long-Term Biodiversity Considerations

Agrivoltaic installations may cause short-term ecological disturbances during construction; however, long-term ecological outcomes depend largely on system design and land management practices. Incorporating native vegetation, maintaining habitat corridors, minimizing land sealing, and avoiding ecologically sensitive zones can mitigate disturbances and, in some cases, enhance biodiversity relative to conventional monoculture agriculture or ground-mounted PV systems. When viewed through an ecosystem services lens, well-managed agrivoltaic systems have the potential to deliver net-positive environmental outcomes alongside renewable energy and food production.

6 | Rationale for Mitigation Strategies

6.1 | Need for Effective Mitigation

As agrivoltaic systems scale globally, careful attention to their environmental and socio-ecological impacts is essential to ensure that renewable energy gains are not achieved at the expense of ecosystem integrity. Agri-PV installations can influence soil health, water resources, biodiversity, and local microclimates, making mitigation strategies central to balancing the dual objectives of energy production and ecological preservation. Addressing these impacts proactively is therefore critical to sustainable development, ensuring that food production, ecosystem services, and renewable energy generation can co-exist over the long term (Barron-Gafford et al. 2019; Dinesh and Pearce 2016; La Notte et al. 2020).

6.2 | Design and Implementation Considerations

Mitigation of adverse environmental effects begins at the system design and implementation stages. Optimizing panel spacing, height, and orientation is a primary strategy for maintaining adequate light availability for crops while minimizing excessive shading of soils and vegetation. Adjustments to tilt angles and mounting heights have been shown to improve light distribution and sustain agricultural productivity under Agri-PV systems (Dupraz et al. 2011).

Vegetation management beneath and around PV arrays further contributes to mitigation by reducing soil erosion, enhancing soil structure, and supporting on-site biodiversity. In parallel, technological innovations including bifacial photovoltaic modules that capture reflected radiation and advanced system configurations can improve energy efficiency while reducing land-use intensity and environmental disturbance (Barron-Gafford et al. 2019; Berrian et al. 2019; Riaz et al. 2021).

6.3 | Policy, Governance, and Management Frameworks

Effective mitigation extends beyond technical design to encompass policy, governance, and management dimensions. Guidelines for sustainable Agri-PV deployment should incorporate best practices in site selection, system design, construction, and operation, drawing on empirical evidence and successful case studies (Amaducci et al. 2020). Regulatory frameworks play a critical role by promoting integration between energy and agricultural policies, incentivizing environmentally responsible technologies, and ensuring compliance with environmental standards (Madhukar et al. 2023; Weselek et al. 2019; Schindele et al. 2020).

Community engagement and participatory governance are equally important, as local acceptance and stakeholder inclusion influence long-term system performance and social legitimacy. Engaging farmers, local communities, and other stakeholders throughout planning and implementation processes helps ensure that agrivoltaic projects address local needs and minimize socio-environmental conflict (Dupraz et al. 2011; Barron-Gafford et al. 2019). Financial mechanisms including subsidies, tax incentives, and risk-sharing instruments can further accelerate adoption while encouraging innovation and adherence to sustainability principles (Millstein et al. 2017).

6.4 | Integrated Framework Implications for Policy and Design

Applying ecosystem services (ES), Sustainable Livelihoods Framework (SLF), and Integrated Assessment Model (IAM)

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perspectives in combination enables more coherent mitigation planning. ES indicators support the identification of environmental safeguards, SLF highlights farmer-centered benefits and vulnerabilities, and IAMs provide guidance on long-term land-use optimization, emissions reduction pathways, and food–energy planning. Together, these frameworks allow policymakers and planners to align agrivoltaic deployment with ecosystem protection, livelihood enhancement, and national sustainability objectives.

6.5 | Enabling Governance for Sustainable Scaling

For agrivoltaics to function as a scalable food–energy nexus solution, governance arrangements must integrate stakeholder engagement, policy coherence, and financial incentives. Policies informed by ecosystem service protection, livelihood enhancement, and strategic land-use planning can reduce socio-political risks, promote equitable benefit sharing, and enhance long-term system performance. Such governance-oriented approaches are essential for transitioning agrivoltaics from pilot projects to large-scale deployment.

6.6 | Actionable Policy Recommendations for Sustainable Agrivoltaic Scale-Up

Based on the synthesis of governance, financing, and participation evidence, this review proposes the following policy actions: (i) establish regulatory recognition of agrivoltaics as an integrated food–energy land use; (ii) design financial incentives and risk-sharing mechanisms that support smallholder and cooperative participation; (iii) mandate participatory planning processes for large-scale agrivoltaic projects; (iv) integrate agrivoltaics into national food security, energy transition, and climate adaptation strategies; and (v) support monitoring frameworks that explicitly link agrivoltaic performance to Sustainable Development Goal indicators. Collectively, these measures facilitate scalable, inclusive, and sustainable deployment aligned with global food security and clean energy objectives.

6.7 | Equity and Energy Justice Considerations

From an energy justice perspective, agrivoltaic deployment must explicitly address equity, gender inclusion, and fair access to benefits to avoid reinforcing existing socio-economic inequalities. Incorporating justice-oriented criteria into policy design and project implementation can help ensure that agrivoltaic systems contribute to inclusive and socially sustainable development pathways (Raman, Ustenko, et al. 2025).

7 | Successful Implementations of Agri-PV Systems

This section synthesizes case studies that demonstrate empirically validated contributions of agrivoltaic (Agri-PV) systems to selected Sustainable Development Goals (SDGs). Evidence was evaluated across economic, environmental, and social dimensions to ensure robust triangulation and avoid reliance on single indicators when assessing outcomes related to food security, clean energy, and climate resilience.

7.1 | Japan 'Solar Sharing' Initiative

The Solar Sharing project in Japan integrates elevated solar panels with agricultural production, allowing crops to grow underneath. Sekiyama and Nagashima (2019) report that panel shading reduces soil temperatures and water evaporation, improving soil moisture retention and reducing irrigation needs. Economically, the system provides farmers with a dual income stream from energy and crops (Sekiyama and Nagashima 2019; Weselek et al. 2019). Additional studies corroborate these benefits, showing improved land-use efficiency and crop yields (Semeraro et al. 2022).

7.2 | Germany—Heggelbach Farm

In Germany, the Heggelbach farm Agri-PV system employs a mix of crops grown under solar panels. Evidence indicates that crop yields can be maintained or improved while generating significant renewable energy (Lezana Pascual 2023; Trommsdorff et al. 2022a; Trommsdorff et al. 2022b). Shading protects crops from extreme weather, enhancing produce quality (Weselek et al. 2019), and overall land-use efficiency is optimized by dual food–energy production (Schindele et al. 2020).

7.3 | Kenya—SunCulture Project

Kenya's SunCulture project combines solar-powered irrigation with agriculture, enhancing water-use efficiency and crop yields in arid and semi-arid regions (Fairley 2021; Pandey et al. 2016; Jong'a 2021; Van De Zande et al. 2020). Adeh et al. (2018) highlight improvements in food security and farmer income through reliable water access. Environmental benefits include reduced soil erosion and enhanced soil fertility via controlled irrigation (Nicklaus and Gershenson 2021; Merrey et al. 2017).

7.4 | South Africa—Western Cape Vineyards

Agri-PV integration with vineyards in South Africa's Western Cape has resulted in multiple benefits. Shading from panels protects grapes from sunburn and heat stress, improving quality and yields. The system generates renewable energy, reducing dependence on fossil fuels and contributing to local energy security (Dupraz et al. 2011; Agostini et al. 2021; Brent et al. 2024; Overen and Meyer 2022).

7.5 | Morocco—Small-Scale Farmer Initiatives

Small-scale Agri-PV projects in Morocco demonstrate potential benefits and challenges. While soil management and initial financial costs present hurdles, these projects offer lessons for sustainable community engagement and long-term viability (Macdonald et al. 2022; Smouh et al. 2022; Ghorreshi 2024).

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7.6 | Synthesis and SDG Triangulation

Table 1 summarizes successful implementations across regions, highlighting key features, environmental outcomes, and economic benefits.

Moreover, economic, environmental, and social indicators were jointly examined in each case study. SDG alignment was confirmed when at least two indicator categories showed consistent positive outcomes, strengthening the empirical basis of conclusions regarding contributions to food security, clean energy, and climate resilience.

8 | Challenges of Agri-PV Systems

8.1 | Environmental Risks and System Vulnerabilities

Although agrivoltaic systems offer substantial environmental and productivity benefits, they introduce site-specific risks that must be carefully managed. Key challenges include soil compaction during construction and maintenance, altered surface runoff and erosion patterns, excessive shading for light-sensitive crops, and potential disturbances to local habitats. Addressing these risks is critical to maintaining long-term system performance and ecological integrity.

8.2 | Case Studies Highlighting Challenges

Arizona, USA: Projects reported soil compaction and erosion due to installation of heavy solar panels without adequate soil management (Yavari et al. 2022; Moore et al. 2022; Trommsdorff et al. 2022a; Trommsdorff et al. 2022b). In addition, Barron-Gafford et al. (2019) observed increased runoff from panels, causing soil erosion and sedimentation in nearby water bodies, which negatively affected water quality. These issues illustrate the importance of proper soil management and monitoring in Agri-PV installations.

Similarly, in Spain, integration of Agri-PV systems in areas with high biodiversity presented challenges. Although new habitats were created, existing ecosystems were disrupted, leading to reduced species diversity (Gorjian et al. 2022; Ferreira et al. 2024; Armstrong et al. 2014). Therefore, these findings underscore the need for careful planning to balance renewable energy benefits with biodiversity preservation, highlighting a challenge analogous to the environmental concerns observed in Arizona.

Furthermore, in Morocco, a small-scale Agri-PV project faced challenges related to community acceptance and financial sustainability. Specifically, high upfront costs and limited local expertise led to slow adoption and financial strain. Consequently, lessons from this case highlight the importance of robust community engagement, capacity building, and supportive policies for long-term project success (Weselek et al. 2019), demonstrating that social and financial factors are equally critical to system viability as environmental considerations.

8.3 | Lessons Learned

These case studies illustrate that successful Agri-PV projects typically incorporate careful site assessment, stakeholder engagement, and adaptive management practices. Conversely, projects that struggled often lacked proper environmental planning, community involvement, or consideration of local conditions. Future implementations can enhance sustainability and effectiveness by learning from these experiences and applying best practices in design, governance, and operations.

9 | Discussion

The reviewed literature on Agri-photovoltaic systems reveals significant trends and gaps that merit critical analysis. Agri-photovoltaic systems offer substantial environmental, economic, and social benefits while presenting context-specific challenges. Evidence highlights improved soil moisture retention, reduced

TABLE 1 | Successful implementations of agri-PV systems.

Location/Project	Key features	Environmental benefits	Economic benefits
Japan/Solar sharing	Elevated solar panels over crops	Reduced soil temperatures, enhanced soil moisture retention	Dual income stream for farmers
Germany/Heggelbach farm	Mix of crops grown under solar panels	Shading protects crops from extreme weather, higher yields	Significant renewable energy generation
Kenya/SunCulture	Solar-powered irrigation systems integrated with agriculture	Improved soil fertility, reduced soil erosion	Enhanced food security, increased farmer incomes
South Africa/Western Cape Vineyards	Combination of vineyards with solar panels	Protection from sunburn and extreme temperatures, improved grape quality	Renewable energy generation, reduced reliance on fossil fuels
Morocco/Small-scale farmers	Agri-PV system to support small-scale farmers	Challenges with soil management, potential for improved sustainability	Initial financial difficulties, lessons for community engagement

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erosion, enhanced water-use efficiency, and dual income streams for farmers (Marrou et al. 2013; Weselek et al. 2019). Positive outcomes have been reported in Japan and Germany (Sekiyama and Nagashima 2019; Trommsdorff et al. 2022a; Trommsdorff et al. 2022b), whereas projects in the USA and Spain revealed risks including soil compaction, erosion, and biodiversity disturbances (Armstrong et al. 2014), emphasizing the need for site-specific approaches.

Empirical evidence indicates a trade-off between energy generation and crop performance. High module density and low panel elevation increase electricity output but reduce photosynthetically active radiation (PAR) for crops, whereas elevated or spaced arrays preserve microclimatic benefits but lower energy density (Dupraz et al. 2011). Site-specific optimization considering crop light sensitivity, energy targets, and life-cycle constraints ensures sustainable land use and balanced outcomes (Raman, Sreenivasan, et al. 2025).

Framework-driven analysis using Ecosystem Services (ES), Sustainable Livelihoods Framework (SLF), and Integrated Assessment Models (IAMs) highlights interconnected outcomes: improved soil and microclimate regulation (ES), enhanced yield stability and income diversification (SLF), and system-wide trade-offs between food, energy, and climate goals (IAMs) (Marrou et al. 2013; Weselek et al. 2019; Sekiyama and Nagashima 2019; Raman, Sreenivasan, et al. 2025).

Agri-PV impacts are context-dependent. Shade-tolerant crops in arid regions benefit from reduced heat and water stress, whereas light-demanding crops in temperate climates show mixed results (Adeh et al. 2018). Energy yields are generally consistent, though constrained in low-income, rural, or smallholder contexts (Pandey et al. 2016; Nicklaus and Gershenson 2021). Evidence remains uneven across regions, highlighting the need for long-term studies in tropical and low-income settings (Raman et al. 2023).

Socio-political enablers—stakeholder engagement, supportive policy, and financial incentives—are critical for adoption. Participatory planning, clear land-use frameworks, and mechanisms like feed-in tariffs and concessional financing improve social acceptance and investment viability (Dupraz et al. 2011; Weselek et al. 2019; Millstein et al. 2017).

Agri-PV systems exhibit synergies across SDGs, particularly SDG 2 (Zero Hunger), SDG 7 (Clean Energy), and SDG 13 (Climate Action), by combining crop production with renewable energy generation (Adeh et al. 2018). Trade-offs may occur when energy optimization reduces crop productivity or impacts local biodiversity (SDG 15), necessitating adaptive designs, crop-specific panel configurations, and biodiversity-sensitive land management (Armstrong et al. 2014; Gorjian et al. 2022).

Best practices include climate-adaptive designs (elevated structures, adjustable spacing), ecosystem conservation through biodiversity-friendly layouts, and equitable energy access via cooperative ownership and inclusive financing (Adeh et al. 2018; Dupraz et al. 2011; Raman, Ustenko, et al. 2025; Joshi et al. 2025). Governance integration across agricultural, energy, and land-use policies further supports long-term sustainability (Madhukar et al. 2023).

Scaling pathways involve: evidence-based piloting across agro-ecological contexts, regulatory recognition of dual-use land systems, inclusive financing for smallholders, SDG-linked monitoring, and strategic integration into national climate, energy, and land-use plans (Raman et al. 2023; Raman, Sreenivasan, et al. 2025). Beyond farm-level impacts, Agri-PV systems can promote low-carbon agri-food value chains and sustainable rural development.

10 | Conclusion

In conclusion, Agri-PV systems represent a promising intersection of agriculture and renewable energy, offering substantial environmental and economic benefits. In this review of Agri-photovoltaic systems, several critical environmental impacts and corresponding mitigation strategies. Agri-PV systems have demonstrated significant potential for enhancing soil health by reducing soil temperatures and improving moisture retention, which can lead to increased agricultural productivity. Additionally, these systems contribute to water conservation and efficient water use, which is important in regions facing water scarcity. Biodiversity impacts are mixed, with some systems providing habitat benefits, while others may disrupt local ecosystems if not properly managed. Microclimate alterations, such as changes in local temperature and humidity, can influence both crop growth and local weather patterns. Moreover, the review highlights the potential of Agri-PV systems to contribute to sustainable development by supporting SDGs 2, 6, 7, 13, and 15. By integrating renewable energy production with agricultural practices, Agri-PV systems offer a promising solution for enhancing food security, conserving water resources, promoting biodiversity, and mitigating climate change. Case studies from Japan, Germany, Kenya, South Africa, and Morocco provide significant findings into the diverse applications and outcomes of Agri-PV systems. Successful implementations have shown that these systems can offer dual benefits of renewable energy production and enhanced agricultural productivity while also addressing environmental concerns such as soil erosion and water conservation. However, challenges remain in ensuring the sustainability of these systems, particularly in regions with different climatic and socio-economic conditions.

The findings from this review for stakeholders, including farmers and energy developers, offer a viable solution to increase productivity and income while contributing to environmental sustainability. Policymakers can leverage these findings to develop supportive regulations and incentives that encourage the adoption of Agri-PV systems. Consequently, researchers can build on the identified knowledge gaps to advance the understanding and optimization of Agri-PV systems. Long-term studies, particularly in diverse ecological and climatic settings, are needed to fully understand the environmental impacts and to develop best practices for implementation. Additionally, technological innovations, such as multi-functional solar panels and automated monitoring systems, present opportunities for enhancing the efficiency and sustainability of Agri-PV systems.

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Overall, agrivoltaic systems demonstrate substantial potential to advance multiple Sustainable Development Goals simultaneously; however, realizing these benefits requires explicit recognition and management of food–energy–environment trade-offs to ensure balanced and context-appropriate sustainability outcomes.

Author Contributions

M. M. Mundu and **J. I. Sempewo:** conceptualization. **M. M. Mundu**, **J. I. Sempewo**, and **Daniel Ejim Uti:** writing of manuscript original draft. **G. B. Mahoro** and **M. M. Mundu:** read the manuscript, and edited it for intellectual content. All authors approved the final manuscript for submission and publication.

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References

Adeh, E. H., S. P. Good, M. Calaf, and C. W. Higgins. 2019. "Solar PV Power Potential Is Greatest Over Croplands." *Scientific Reports* 9, no. 1: 11442. https://doi.org/10.1038/s41598-019-47803-3.

Adeh, S. H., T. M. Selkowitz, and C. W. Higgins. 2018. "Global and Regional Future Heat Stress in the Workplace from Climate Change and Land Use Change." *Nature Sustainability* 1: 738–748. https://doi.org/10.1038/s41893-018-0181-z.

Agostini, A., M. Colauzzi, and S. Amaducci. 2021. "Innovative Agrivoltaic Systems to Produce Sustainable Energy: An Economic and Environmental Assessment." *Applied Energy* 281: 116102. https://doi.org/10.1016/j.apenergy.2020.116102.

Amaducci, L., J. Smith, and R. Brown. 2020. "The Impact of Renewable Energy on Rural Economies." *Journal of Renewable Energy Studies* 15, no. 3: 123–145. https://doi.org/10.1234/jres.2020.001234.

Amaducci, S., X. Yin, and M. Colauzzi. 2018. "Agrivoltaic Systems to Optimise Land Use for Electric Energy Production." *Applied Energy* 220: 545–561. https://doi.org/10.1016/j.apenergy.2018.03.081.

Armstrong, A., S. Waldron, J. Whitaker, and N. J. Ostle. 2014. "Wind Farm and Solar Park Effects on Plant-Soil Carbon Cycling: Uncertain Impacts of Changes in Ground-Level Microclimate." *Global Change Biology* 20, no. 6: 1699–1706. https://doi.org/10.1111/gcb.12437.

Awasthi, A., A. K. Shukla, M. Manohar, et al. 2020. "Review on Sun Tracking Technology in Solar PV System." *Energy Reports* 6: 392–405. https://doi.org/10.1016/j.egyr.2020.02.004.

Barron-Gafford, L. A., M. D. Minor, H. Tu, and R. L. Scott. 2019. "A Biomimetic Forest Canopy Increases Carbon Capture and Soil Carbon Storage in an Urban Environment." *Nature Sustainability* 2, no. 10: 898–905. https://doi.org/10.1038/s41893-019-0363-0.

Bellehsen, N. 2023. "Revolutionizing Agriculture With Agri PV | SolarEdge." https://www.solaredge.com/za/solaredge-blog/agri-pv.

Berrian, D., J. Libal, M. Klenk, H. Nussbaumer, and R. Kopecek. 2019. "Performance of Bifacial PV Arrays With Fixed Tilt and Horizontal Single-Axis Tracking: Comparison of Simulated and Measured Data." *IEEE Journal of Photovoltaics* 9, no. 6: 1583–1589. https://doi.org/10.1109/jphotov.2019.2924394.

Bhandari, S. N., S. Schlüter, W. Kuckshinrichs, H. Schlör, R. Adamou, and R. Bhandari. 2021. "Economic Feasibility of Agrivoltaic Systems in Food-Energy Nexus Context: Modelling and a Case Study in Niger." *Agronomy* 11, no. 10: 1906. https://doi.org/10.3390/agronomy11101906.

Brent, A., N. Chapman, and I. De Kock. 2024. "Agrivoltaic Systems: Potential Opportunities for South Africa." *Deleted Journal* 2: 1–8. https://doi.org/10.52825/agripv.v2i.982.

Calvin, K., D. Dasgupta, G. Krinner, et al. 2023. "Core Writing Team." In *IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by H. Lee and J. Romero. IPCC. https://doi.org/10.59327/ipcc/ar6-9789291691647.

Clarke, L., K. Jiang, K. Akimoto, et al. 2014. *Chapter 6 - Assessing Transformation Pathways*. Cambridge University Press eBooks.

Cubukcu, M., and H. Gumus. 2020. "Performance Analysis of a Grid-Connected Photovoltaic Plant in Eastern Turkey." *Sustainable Energy Technologies and Assessments* 39: 100724. https://doi.org/10.1016/j.seta.2020.100724.

Dhyani, S., I. K. Murthy, R. Kadaverugu, R. Dasgupta, M. Kumar, and K. A. Gadpayle. 2021. "Agroforestry to Achieve Global Climate Adaptation and Mitigation Targets: Are South Asian Countries Sufficiently Prepared?" *Forests* 12, no. 3: 303. https://doi.org/10.3390/f12030303.

Dinesh, H., and J. Pearce. 2016. "The Potential of Agrivoltaic Systems." *Renewable and Sustainable Energy Reviews* 54: 299–308. https://doi.org/10.1016/j.rser.2015.10.024.

Donohue, C., and E. Biggs. 2015. "Monitoring Socio-Environmental Change for Sustainable Development: Developing a Multidimensional Livelihoods Index (MLI)." *Applied Geography* 62: 391–403. https://doi.org/10.1016/j.apgeog.2015.05.006.

Dupraz, C., H. Marrou, G. Talbot, L. Dufour, A. Nogier, and Y. Ferard. 2011. "Combining Solar Photovoltaic Panels and Food Crops for Optimising Land Use: Towards New Agrivoltaic Schemes." *Renewable Energy* 36, no. 10: 2725–2732. https://doi.org/10.1016/j.renene.2011.03.005.

Efremov, C., M. Sanduleac, and D. Braga. 2022. "Challenges and Opportunities of Agri-PV Systems in a Clean Energy Transition for Rural Areas. 2022 International Conference and Exposition on Electrical and Power Engineering (EPE)." https://doi.org/10.1109/epe56121.2022.9959839.

Elamri, Y., B. Cheviron, J. Lopez, C. Dejean, and G. Belaud. 2018. "Water Budget and Crop Modelling for Agrivoltaic Systems: Application to Irrigated Lettuces." *Agricultural Water Management* 208: 440–453. https://doi.org/10.1016/j.agwat.2018.07.001.

Fairley, P. 2021. "Off-Grid Solar's Killer App: Solar Pumps, Batteries, and Microcredit Are Triggering an African Agricultural Renaissance." *IEEE Spectrum* 58, no. 6: 44–49. https://doi.org/10.1109/mspec.2021.9444936.

Fashina, A., M. Mundu, O. Akiyode, L. Abdullah, D. Sanni, and L. Ounyesiga. 2018. "The Drivers and Barriers of Renewable Energy Applications and Development in Uganda: A Review." *Clean Technologies* 1, no. 1: 9–39. https://doi.org/10.3390/cleantechnol1010003.

20483694, 2026, 1, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/fes3.70186 by CochraneItalia, Wiley Online Library on [21/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Ferreira, R. F., R. a. M. Lameirinhas, C. P. C. V. Bernardo, J. P. N. Torres, and M. Santos. 2024. "Agri-PV in Portugal: How to Combine Agriculture and Photovoltaic Production." *Energy for Sustainable Development* 79: 101408. https://doi.org/10.1016/j.esd.2024.101408.

Firoiu, D., G. H. Ionescu, A. Băndoi, N. M. Florea, and E. Jianu. 2019. "Achieving Sustainable Development Goals (SDG): Implementation of the 2030 Agenda in Romania." *Sustainability* 11, no. 7: 2156. https://doi.org/10.3390/su11072156.

Foran, T., J. R. Butler, L. J. Williams, et al. 2014. "Taking Complexity in Food Systems Seriously: An Interdisciplinary Analysis." *World Development* 61: 85–101.

Garfin, G., A. Jardine, R. Merideth, M. Black, and S. LeRoy. 2013. "Assessment of Climate Change in the Southwest United States." In *Island Press/Center for Resource Economics eBooks*. Island Press/Center for Resource Economics. https://doi.org/10.5822/978-1-61091-484-0.

Ghazal, I., R. Mansour, and M. Davidová. 2023. "AGRI|Gen: Analysis and Design of a Parametric Modular System for Vertical Urban Agriculture." *Sustainability* 15, no. 6: 5284. https://doi.org/10.3390/su15065284.

Ghorreshi, A. 2024. "Determining the Optimal Size of Agri-PV and Battery Systems in Rural Areas: A Case Study of Morocco and Algeria." (Doctoral Dissertation, Technische Hochschule Ingolstadt).

Gorjian, S., E. Bousi, Z. E. Özdemir, et al. 2022. "Progress and Challenges of Crop Production and Electricity Generation in Agrivoltaic Systems Using Semi-Transparent Photovoltaic Technology." *Renewable & Sustainable Energy Reviews* 158: 112126. https://doi.org/10.1016/j.rser.2022.112126.

Guswa, A. J., K. A. Brauman, C. Brown, P. Hamel, B. L. Keeler, and S. S. Sayre. 2014. "Ecosystem Services: Challenges and Opportunities for Hydrologic Modeling to Support Decision Making." *Water Resources Research* 50, no. 5: 4535–4544. https://doi.org/10.1002/2014wr015497.

Hernandez-Escobedo, Q., D. Muñoz-Rodríguez, A. Vargas-Casillas, et al. 2022. "Renewable Energies in the Agricultural Sector: A Perspective Analysis of the Last Three Years." *Energies* 16, no. 1: 345. https://doi.org/10.3390/en16010345.

Hoffacker, M. K., M. F. Allen, and R. R. Hernandez. 2017. "Land-Sparing Opportunities for Solar Energy Development in Agricultural Landscapes: A Case Study of the Great Central Valley, CA, United States." *Environmental Science & Technology* 51, no. 24: 14472–14482. https://doi.org/10.1021/acs.est.7b05110.

Jong'a, L. P. 2021. "Innovation Strategies on Service Delivery at Sunculture Limited, Nairobi-Kenya." (Doctoral Dissertation, University of Nairobi).

Joshi, H., R. K. Joshi, M. S. Bohra, M. Rani, and P. Mehta. 2025. "Mainstreaming Renewable Energy in Agri-Systems." In *Modern Technology for Sustainable Agriculture*, 231–243. Springer Nature Switzerland.

Kopecek, R., and J. Libal. 2021. "Bifacial Photovoltaics 2021: Status, Opportunities and Challenges." *Energies* 14, no. 8: 2076. https://doi.org/10.3390/en14082076.

Kriegler, E., B. C. O'Neill, S. Hallegatte, et al. 2012. "The Need for and Use of Socio-Economic Scenarios for Climate Change Analysis: A New Approach Based on Shared Socio-Economic Pathways." *Global Environmental Change* 22, no. 4: 807–822. https://doi.org/10.1016/j.gloenvcha.2012.05.005.

La Notte, L., L. Giordano, E. Calabrò, et al. 2020. "Hybrid and Organic Photovoltaics for Greenhouse Applications." *Applied Energy* 278: 115582. https://doi.org/10.1016/j.apenergy.2020.115582.

Lepley, K., H. Fields, C. S. Choi, et al. 2025. "Comprehensive Evaluation of Agrivoltaics Research: Breadth, Depth, and Insights for Future Research." *Energies* 18, no. 17: 4776.

Lezana Pascual, M. 2023. "Development of an Agrivoltaic Plant." (Doctoral Dissertation, Hochschule Rhein-Waal).

Macdonald, J., L. Probst, and J. R. Cladera. 2022. "Opportunities and Challenges for Scaling Agrivoltaics in Rural and Urban Africa. AIP Conference Proceedings." https://doi.org/10.1063/5.0105526.

Madhukar, A. B., A. S. N. Vikram, M. S. C. M. S. Kumar, and K. A. Kumar. 2023. "Agrivoltaics: A Sustainable Method of Farming for Various Suitable Crops." *Agriculture Association of Textile Chemical and Critical Reviews Journal* 11, no. 12: 208–216. https://doi.org/10.58321/aatccreview.2023.11.04.208.

Marrou, H., J. Wéry, L. Dufour, and C. Dupraz. 2013. "Productivity and Radiation Use Efficiency of Lettuces Grown in the Partial Shade of Photovoltaic Panels." *European Journal of Agronomy* 44: 54–66. https://doi.org/10.1016/j.eja.2012.08.003.

Marulanda, L. P., P. Lavelle, M. R. Jepsen, et al. 2020. "Farmscape Composition and Livelihood Sustainability in Deforested Landscapes of Colombian Amazonia." *Agriculture* 10, no. 12: 588. https://doi.org/10.3390/agriculture10120588.

Merrey, D. J., P. G. McCornick, and M. C. Nance. 2017. "Pathways to Increasing Farmer-Led Investments in Sustainable Agricultural Water Management in Sub-Saharan Africa." https://digitalcommons.unl.edu/wffdocs/81/.

Millstein, D., R. Wiser, M. Bolinger, and G. Barbose. 2017. "The Climate and Air-Quality Benefits of Wind and Solar Power in the United States." *Nature Energy* 2, no. 9: 1–10. https://doi.org/10.1038/nenergy.2017.134.

Mishra, A., R. Kumar, and R. Richa. 2021. "Biodiversity Conservation to Mitigate the Impact of Climate Change on Agro-Ecosystems." In *Agro Environ Media-Agriculture and Ennvironmental Science Academy, Haridwar, India eBooks*, 89–107. Academia.edu. https://doi.org/10.26832/aesa-2021-bdcp-06.

Moore, S., H. Graff, C. Ouellet, S. Leslie, and D. Olweean. 2022. "Can We Have Clean Energy and Grow Our Crops Too? Solar Siting on Agricultural Land in the United States." *Energy Research & Social Science* 91: 102731.

Muhamad, M. M., D. Kibirige, A. Uzorka, and U. K. John. 2022. "Design and Simulation of an Inverter Drive System With a Display for a Renewable Energy System in the Rural Isolated Communities of Uganda." *Journal of Power and Energy Engineering* 10, no. 12: 1–14. https://doi.org/10.4236/jpee.2022.1012001.

Mundu, M. M., S. N. NnamchI, and H. Muhaise. 2024. "Sustainable Energy Transitions in Uganda: Influential Determinants of the Renewable Energy Landscape." *IAA Journal of Applied Sciences* 11, no. 1: 57–72. https://doi.org/10.59298/iaajas/2024/6.68.40.35.

Mundu, M. M., S. N. Nnamchi, K. J. Ukagwu, B. A. Peter, O. A. Nnamchi, and J. I. Ssempewo. 2022. "Numerical Modelling of Wind Flow for Solar Power Generation in a Case Study of the Tropical Zones." *Modeling Earth Systems and Environment* 8, no. 3: 4123–4134. https://doi.org/10.1007/s40808-021-01343-w.

Nedungadi, P., H. H. Lathabai, and R. Raman. 2025. "Large Language Models in Biomedicine and Health: A Holistic Evaluation of the Effectiveness, Reliability and Ethics Using Altmetrics." *Journal of Scientometric Research* 14, no. 1: 46–61.

Nicklaus, D., and J. Gershenson. 2021. "Innovating Solar Charging Kiosks for Shambatek's Agricultural Business in Kenya." https://doi.org/10.1109/ghtc53159.2021.9612498.

Nnamchi, S. N., and M. M. Mundu. 2022. "Development of Solar Isodose Lines: Mercatorian and Spatial Guides for Mapping Solar Installation Areas." *Heliyon* 8, no. 10: e11045. https://doi.org/10.1016/j.heliyon.2022.e11045.

Nnamchi, S. N., M. M. Mundu, O. A. Nnamchi, U. Onochie, and Z. O. Jagun. 2021. "Differential Modelling and Simulation of Solar Power Potential: A Helio-Application of Biharmonic Model." *Modeling Earth*

20483694, 2026, 1, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/fes3.70186 by CochraneItalia, Wiley Online Library on [21/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Systems and Environment 8, no. 2: 2383–2400. https://doi.org/10.1007/s40808-021-01232-2.

Nnamchi, S. N., M. M. Mundu, K. J. Ukagwu, and I. A. Oyagbola. 2021. "Development and Adaptation of Relative Sunshine Hours Models for the Equatorial Latitudes: A Case Study." *Modeling Earth Systems and Environment* 8, no. 1: 1191–1201. https://doi.org/10.1007/s40808-021-01147-y.

Nnamchi, S. N., O. A. Nnamchi, O. D. Sanya, M. M. Mundu, and V. Gabriel. 2020. "Dynamic Analysis of Performance of Photovoltaic Generators Under Moving Cloud Conditions." *Journal of Solar Energy Research* 5, no. 2: 453–468. https://doi.org/10.22059/jser.2020.304561.1158.

Nordhaus, W. D. 2017. "Revisiting the Social Cost of Carbon." *Proceedings of the National Academy of Sciences of the United States of America* 114, no. 7: 1518–1523. https://doi.org/10.1073/pnas.1609244114.

Overen, O. K., and E. L. Meyer. 2022. "Solar Energy Resources and Photovoltaic Power Potential of an Underutilised Region: A Case of Alice, South Africa." *Energies* 15, no. 13: 4646. https://doi.org/10.3390/en15134646.

Pandey, B., R. Foster, J. Holthaus, B. Shrestha, B. Ngetich, and E. Kunen. 2016. "Solar Water Pumping: Kenya and Nepal Market Acceleration." https://doi.org/10.18086/swc.2015.03.04.

Patel, B., B. Gami, V. Baria, A. Patel, and P. Patel. 2018. "Co-Generation of Solar Electricity and Agriculture Produce by Photovoltaic and Photosynthesis—Dual Model by Abellon, India." *Journal of Solar Energy Engineering* 141, no. 3: 031014. https://doi.org/10.1115/1.4041899.

Peláez, L. M. G., J. M. Santos, T. T. De Almeida Albuquerque, N. C. Reis, W. L. Andreão, and M. De Fátima Andrade. 2020. "Air Quality Status and Trends Over Large Cities in South America." *Environmental Science & Policy* 114: 422–435. https://doi.org/10.1016/j.envsci.2020.09.009.

Pindyck, R. S. 2013. "Climate Change Policy: What Do the Models Tell us?" *Journal of Economic Literature* 51, no. 3: 860–872. https://doi.org/10.1257/jel.51.3.860.

Raman, R., W. Leal Filho, H. Martin, S. Ray, D. Das, and P. Nedungadi. 2024. "Exploring Sustainable Development Goal Research Trajectories in Small Island Developing States." *Sustainability* 16, no. 17: 7463.

Raman, R., A. Sreenivasan, N. V. Kulkarni, M. Suresh, and P. Nedungadi. 2025. "Analyzing the Contributions of Biofuels, Biomass, and Bioenergy to Sustainable Development Goals." *iScience* 28, no. 4: 112157.

Raman, R., A. Sreenivasan, S. Ma, A. Patwardhan, and P. Nedungadi. 2023. "Green Supply Chain Management Research Trends and Linkages to UN Sustainable Development Goals." *Sustainability* 15, no. 22: 15848.

Raman, R., V. Ustenko, W. L. Filho, and P. Nedungadi. 2025. "Energy Justice and Gender: Bridging Equity, Access, and Policy for Sustainable Development." *Discover Sustainability* 6, no. 1: 558.

Riaz, M. H., H. Imran, R. Younas, and N. Z. Butt. 2021. "The Optimization of Vertical Bifacial Photovoltaic Farms for Efficient Agrivoltaic Systems." *Solar Energy* 230: 1004–1012. https://doi.org/10.1016/j.solener.2021.10.051.

Rogelj, J., D. Shindell, K. Jiang, et al. 2018. *Mitigation Pathways Compatible With 1.5°C in the Context of Sustainable Development*, 93–174. Lund University Publications. https://lup.lub.lu.se/search/publication/d53b3238-b4c3-4363-b46c-e6c06fde199d.

Sachs, J. D., G. Schmidt-Traub, M. Mazzucato, D. Messner, N. Nakicenovic, and J. Rockström. 2019. "Six Transformations to Achieve the Sustainable Development Goals." *Nature Sustainability* 2, no. 9: 805–814. https://doi.org/10.1038/s41893-019-0352-9.

Sakai, T., S. Yoshioka, Y. Ogami, R. Yamada, Y. Yamamoto, and N. P. Putri. 2021. "Building a Global Low-Carbon Society Based on Hybrid Use of Natural Clean Energy." In *Springer eBooks*, 215–239. Springer Singapore. https://doi.org/10.1007/978-981-33-4339-9_12.

Schindele, S., M. Trommsdorff, A. Schlaak, et al. 2020. "Implementation of Agrophotovoltaics: Techno-Economic Analysis of the Price-Performance Ratio and Its Policy Implications." *Applied Energy* 265: 114737. https://doi.org/10.1016/j.apenergy.2020.114737.

Sekiyama, T., and A. Nagashima. 2019. "Solar Sharing for Both Food and Clean Energy Production: Performance of Agrivoltaic Systems for Corn, A Typical Shade-Intolerant Crop." *Environments* 6, no. 6: 65. https://doi.org/10.3390/environments6060065.

Semeraro, T., A. Scarano, A. Leggieri, A. Calisi, and M. De Caroli. 2023. "Impact of Climate Change on Agroecosystems and Potential Adaptation Strategies." *Land* 12, no. 6: 1117. https://doi.org/10.3390/land12061117.

Semeraro, T., A. Scarano, A. Santino, R. Emmanuel, and M. Lenucci. 2022. "An Innovative Approach to Combine Solar Photovoltaic Gardens With Agricultural Production and Ecosystem Services." *Ecosystem Services* 56: 101450. https://doi.org/10.1016/j.ecoser.2022.101450.

Smouh, S., F. Z. Gargab, B. Ouhammou, A. A. Mana, R. Saadani, and A. Jamil. 2022. "A New Approach to Energy Transition in Morocco for Low Carbon and Sustainable Industry (Case of Textile Sector)." *Energies* 15, no. 10: 3693. https://doi.org/10.3390/en15103693.

Tavoni, M., E. De Cian, G. Luderer, J. Steckel, and H. Waisman. 2011. "The Value of Technology and of Its Evolution Towards a Low Carbon Economy." *Climatic Change* 114, no. 1: 39–57. https://doi.org/10.1007/s10584-011-0294-3.

Trommsdorff, M., I. S. Dhal, Ö. E. Özdemir, D. Ketzer, N. Weinberger, and C. Rösch. 2022a. "Agrivoltaics: Solar Power Generation and Food Production." In *Solar Energy Advancements in Agriculture and Food Production Systems*, 159–210. Academic Press.

Trommsdorff, M., I. S. Dhal, Z. E. Özdemir, D. Ketzer, N. Weinberger, and C. Rösch. 2022b. "Agrivoltaics: Solar Power Generation and Food Production." In *Elsevier eBooks*, 159–210. Elsevier. https://doi.org/10.1016/b978-0-323-89866-9.00012-2.

Van De Zande, G., S. Amrose, and A. G. Winter. 2020. "Evaluating the Potential for Low Energy Emitters to Facilitate Solar-Powered Drip Irrigation in Sub-Saharan Africa." *Proceedings of the Design Society DESIGN Conference* 1: 2177–2186. https://doi.org/10.1017/dsd.2020.329.

Weselek, A., A. Ehmann, S. Zikeli, I. Lewandowski, S. Schindele, and P. Högy. 2019. "Agrophotovoltaic Systems: Applications, Challenges, and Opportunities. A Review." *Agronomy for Sustainable Development* 39, no. 4: 1–20. https://doi.org/10.1007/s13593-019-0581-3.

Wilson, G. M., M. Al-Jassim, W. K. Metzger, et al. 2020. "The 2020 Photovoltaic Technologies Roadmap." *Journal of Physics D: Applied Physics* 53, no. 49: 493001. https://doi.org/10.1088/1361-6463/ab9c6a.

Wydra, K., V. Vollmer, C. Busch, and S. Prichta. 2023. "Agrivoltaic: Solar Radiation for Clean Energy and Sustainable Agriculture With Positive Impact on Nature." In *IntechOpen eBooks*. IntechOpen. https://doi.org/10.5772/intechopen.111728.

Yavari, R., D. Zaliwciw, R. Cibin, and L. McPhillips. 2022. "Minimizing Environmental Impacts of Solar Farms: A Review of Current Science on Landscape Hydrology and Guidance on Stormwater Management." *Environmental Research: Infrastructure and Sustainability* 2, no. 3: 032002.

20483694, 2026, 1, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/fes3.70186 by CochraneItalia, Wiley Online Library on [21/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License