Journal of Innovative Agriculture
Review Article

Agrivoltaics in India: advancing food security, renewable energy, and ecosystem services through integrated land use for sustainable development goals

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Volume: 12, Issue: 4, Pages: 1-9
DOI: https://doi.org/10.37446/jinagri/ra/12.4.2025.1-9
Received: 21 June 2025 / Accepted: 28 September 2025 / Published: 31 December 2025

The world is facing a pressing issue: an increasing population and a shrinking area under cultivation. However, it is unrealistic to increase food production and optimize energy production on existing land. The agrivoltaics system proves to be a panacea for integrating energy production with agriculture. Agrivoltaics is the concept of using the same land for both crop production and solar energy generation. It is defined as agricultural production, such as crop or livestock production, that occurs underneath or adjacent to solar panels. Through photovoltaics, it is possible to co-locate solar and agricultural power on the same land, providing benefits to both the solar and farming industries. This integrated approach enables the simultaneous production of food and electricity by effectively capturing solar radiation. The approach will allow us to address food security problems on the one hand and minimize our dependence on non-renewable sources on the other, thus paving the way for a sustainable environment.

Keywords: *agrivoltaics, food security, renewable energy, ecosystem services, SDGs, India*

Introduction

Agrivoltaics have their roots in the 1980s, when issues of land scarcity, food security, and mounting energy challenges began to attract international attention (Ghasemi et al., 2025). An early proposal to integrate solar energy generation with agriculture can be found by a German physicist, Adolf Goetzberger, pioneer of solar energy, in his 1981 article published in the International Journal of Solar Energy, written with Armin Zastrow, in which he referred to a combination of agriculture and solar energy production, leading to what is known as the agrivoltaics system (Goetzberger & Zastrow, 1982; Braun & Berwind, 2024). Agrivoltaics is considered an influential mechanism for both food production and renewable energy. The principle adheres to its initial goals and aims to ensure more efficient land use, improved energy production, and minimal impact on farming (Time et al., 2024). As a result, studies and experiments on agrivoltaics were spurred, and several arrangements and methods were developed that maximized the benefits of food and renewable energy production. An agrivoltaics revolution in India can be traced back to the early 2000s, when India began seeking alternative energy sources to meet its growing energy demands. The agrivoltaics system offers a solution to reduce competition for land between agriculture and energy generation. Agrivoltaics can improve land-use efficiency while minimizing competition for land use (Jain et al., 2021).

Figure 1. Benefits of adopting agrivoltaics systems

Against the backdrop of the immediate prospects of food insecurity and energy sustainability, the manuscript aimed at investigating the viability of agrivoltaics as a possible solution to such threats, especially in India, which includes the technical issues, types, benefits (Figure 1), and challenges of agrivoltaics, to provide a holistic view of the innovation. An example of a case study from Sitapur, India, will demonstrate the real-life successful practice and the difficulties associated with the introduction of agrivoltaics, which can be of great value to stakeholders and inform their understanding of the development. Moreover, it discusses the future of agrivoltaics in India and how collaborative efforts and supportive policies can help overcome current obstacles and unlock the full potential of this technology. This article adds to the emerging literature on agrivoltaics, offering unique details on its application in India, which has great potential for this technology. It provides useful advice to policymakers, scholars, and practitioners on how to encourage agrivoltaics and achieve sustainable development goals.

Technical aspects of agrivoltaics

Certain technical factors can enhance the productivity of both food and energy production in Agrivoltaics. They are: (1) Solar panel design: Solar panels are fixed on the structures that can rise above the ground so that sufficient light can penetrate to the crops. Monocrystalline and polycrystalline panels are among the most common solar panels used in agrivoltaics (Maity et al., 2025). 2) Spacing: This plays a critical role in the maximization of sunbeams in the field so that the crops can develop with ease. The arrangement should cause minimum disruption to the existing agricultural processes (Zainol-Abidin et al., 2021); (3) Orientation: Solar panels should be oriented in such a way that they can receive the highest amount of solar radiation with minimum shadowing to the crops. The stationary panels are usually oriented to the south. The dynamic, rotating on an axis, panels are oriented in the east-west direction (Abidin et al., 2023); (4) Irrigation and water management: Agrivoltaic systems often use efficient irrigation systems as efficient irrigation systems to reduce water usage and maintain a decent supply of water to crops and enhance the performance of solar panels (Scarano et al., 2025); (5) Crop selection: crops that can grow in partial shade and the conditions created by solar panels are selected comparatively shade-tolerant Crops such as (i) Leafy greens, lettuce, kale and spinach; (ii) Root crops such as radishes, potatoes, beets and carrots; (iii) Fruits such as blueberries and strawberries; (iv) Herbs such as mint, basil and rosemary are considered good candidates and have been determined to grow under the solar panel.

Types of agrivoltaics

In general, there are three approaches in agrivoltaics. They are,

1. Ground-mounted solar panels

The technology is employed in large solar schemes with a generation capacity of more than 5 MW. The benefit is that it allows perennial vegetation and pasture under solar panels. Also, the ground-mounted solar panels leave enough space for animals to graze, thereby increasing their welfare (Saand et al., 2025).

2. Elevated solar panels

This method implies installing the panels at a height of 2.5-5m above the ground. Solar panels on elevated landings are particularly suited to fruit crops, trees, and vine plants such as grapes. The technique allows crops to receive maximum sunlight without hindering growth (Zhang et al., 2025).

3. Solar greenhouses

This method has become common lately. It entails installing solar panels on the roofs of houses. These panels can provide sufficient electrical power to run the greenhouse without compromising crop production much (Zhang et al., 2024). In addition to the above types, other classifications of agrivoltaics are listed in Table 1.

Table 1. Types of agrivoltaics

Parameter	Description	Typical Configuration	Land Use Efficiency	Energy Production	Installation Cost	Maintenance Requirements	Suitable Crops	Environmental Benefits	References
Inter-row Agrivoltaics	Panels in rows, crops between (1-2m height)	Spacings 3-6m, standard ground mount	High, dual use with potential for pollinators	50-100% of standard solar, depends on spacing	Lower, like ground-mounted solar	Standard for solar and agriculture	Shade-tolerant (lettuce, spinach, Legumes, wheat, berries)	Reduced water use, habitat for pollinators	Hasan et al., 2023
Elevated Agrivoltaics	Panels above crops (2-5m height)	Heights 2-5m, spacings 0.71-9.5m	Very high, crops directly under panels	50-80% of standard, less dense arrangement	Higher, due to elevated structures	Higher, complex structures require more care	Wide range (fruits, vegetables, chillies, Spinach, kale, tomatoes)	Crop protection, microclimate benefits	Willockx et al., 2022
Greenhouse Agrivoltaics	Semi-transparent panels on greenhouse roofs	Varies by panel coverage (20-50% of roof)	High, integrated with a controlled environment	20-50% of the roof area, depending on transparency	Integrated, varies by greenhouse design	Standard greenhouse + PV maintenance	Controlled crops (tomatoes, cucumbers, Lemons, sweet oranges)	Energy savings, potential water efficiency	Gnayem et al., 2024

Advantages of agrivoltaics

Agri-voltaics has several benefits. Among these benefits is that crops under the solar panels are protected from harsh weather, such as intense sunlight or hail. According to the research by Barron-Gafford et al. (2019), the tomatoes showed a 50% increase in production under the shade panels, with the effect being more pronounced on the crops planted below them (Figure 1). The colour of the solar panels strongly influences the necessity of irrigation. Drought stress has been mitigated because the crops grown beneath the panels exhibit reduced evapotranspiration. In scenarios where available land for solar panel installation is constrained, as is often the case in European countries, implementing an Agrivoltaics system has been shown to enhance the economic viability of the utilized space (Ramos-Fuentes et al., 2023).

Research has shown that using Agrivoltaics on farms adds more than 30% to land sales value (Majumdar & Pasqualetti, 2018). Agrivoltaic systems can generate more renewable energy, reducing carbon emissions and decreasing the risk of extreme weather events driven by climate change (Barron-Gafford et al., 2019). Given the enormous agricultural footprint, even a 1% conversion of crop area to Agrivoltaics could go a long way toward neutralizing global demand for carbon-intensive energy sources (Collignon, 2025). With the implementation of agrivoltaics, higher revenue per acre can be achieved through the generated electricity, resulting in greater income for the farmer.

Challenges to adopting agrivoltaics systems

Commercial-scale AV systems have been developed in Japan, China, South Korea, Germany, Italy, France, and India. However, these systems still stay in the experimental phase, but due to the different obstacles (Asa et al., 2024) (Figure 2). The above may not be enough to outweigh the initial investment in agrivoltaic installations, which has led farmers to steer away from using this technology. Furthermore, the reluctance of small-scale farmers to modify their agricultural practices has also been a significant impediment to the adoption of this system (Feuerbacher et al., 2022). The scarcity of PV (Photovoltaic) experts and technicians, who are essential for the design and maintenance of this technology, has been identified as a significant impediment to the expansion of renewable energy sources. When installing an agrivoltaic system, proper planning and design are essential to ensure optimal performance. Additionally, high-frequency maintenance of both plants and solar panels is necessary to provide the system's sustainable efficiency (Zainol Abidin et al., 2021). The need for suitable land to accommodate agrivoltaics is another constraint. During land selection, factors such as soil quality, slope, and sufficient sunlight are of primary concern. AV is relatively new, resulting in ignorance, or at least limited awareness, among government officials, farmers, and laypeople of the opportunities it offers and the advantages it provides. Besides, legislation on land tenure and use is widely in place, without consideration of AV systems, along with energy policies. It demands the development of significant policies and laws.

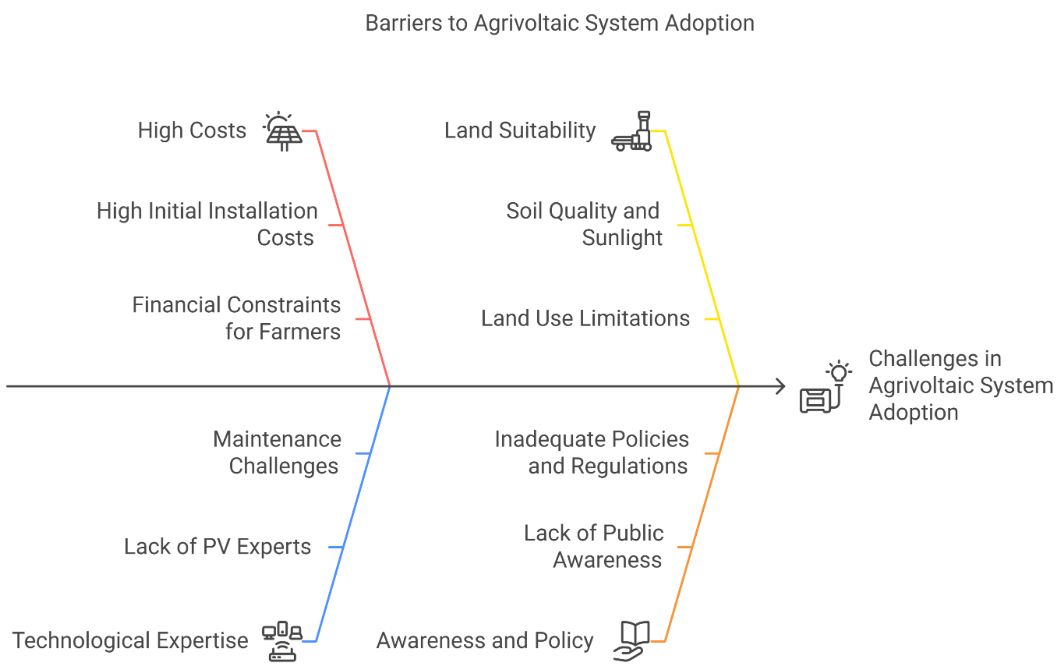

Figure 2. Barriers to adopting an agrivoltaics system

Ecosystem services from agrivoltaics

The term 'agrivoltaics' combines solar photovoltaic (PV) systems with farmland and has been demonstrated to offer several environmental benefits as a cost-effective land use. It has been reported that water can be conserved through reduced soil evaporation and panel shading in the field, with a range of 19 to 47 per cent compared to fields without panels (Ramos-Fuentes et al., 2023). The positive effects of soil health on the environment are well-documented. These include increased organic matter in the soil and reduced soil erosion. Furthermore, elevated systems do not cause extensive soil disturbance (Trommsdorff et al., 2022). A comprehensive overview of the pivotal ecosystem services provided by the agrivoltaics system is presented in Table 2. The efficiency of land use is also increased, with a 70-80% increase in land productivity, thereby enabling both agricultural and energy production (Jain et al., 2021). The integration of clean energy with agriculture has been demonstrated to engender climate resilience (Barron-Gafford et al., 2019).

Table 2. Ecosystem services from agrivoltaics

Ecosystem Service	Ecosystem Services Category	Benefits	References
Water Conservation	Regulating Service	Minimizes soil evaporation by shading the soil with solar panels, boosting water-use efficiency (WUE). Panel cleaning water can be reused to irrigate crops in areas where water is scarce.	Ramos-Fuentes et al., 2023; IISD. (2023)
Soil Health and Erosion Control	Supporting Service	Enhances soil architecture by building up organic matter beneath panels, and minimizes erosion by shielding the land from wind and dust storms. With elevated systems, the land disturbs less soil, thereby saving topsoil.	Trommsdorff et al. (2021); Marrou et al. (2013)
Land-Use Efficiency	Supporting Service	Improves land efficiency by growing food crops and generating solar energy in parallel, maximizing the use of limited arable land.	Jain, P., et al. (2021); Ghosh, A. (2023)
Climate Resilience	Regulating Service	Induces climatic changes by adopting clean energy generation practices, mitigating greenhouse gas (GHG) emissions, and strengthening agricultural resilience against adverse weather events such as heat waves and hail.	Adeh, E. H., et al. (2019); Shahsavari & Akbari (2018)
Biodiversity Support	Supporting Service	Helps pollinator habitats with vegetation panels and possible ecosystem development, which also adds to agricultural biodiversity.	Walston et al. (2022)

Furthermore, pollinator-friendly designs have been shown to support biodiversity. Furthermore, the microclimate is characterized by its stability, which is conducive to mitigating heat stress and enhancing crop growth (Ghosh, 2023). This is evidenced by land equivalent ratios (LER) ranging from 1.67 to 1.93 (Ghosh, 2023).

How Agrivoltaics can contribute to the achievement of SDGs

Agrivoltaics is associated with numerous Sustainable Development Goals (SDGs), thereby contributing to global sustainability. Regarding SDG 7, the implementation of AV has generated clean energy. India has already achieved a solar capacity of 15.9 per cent of the overall installed capacity (MNRE, 2024), with a target of 10,000 MW by 2024. Achieving SDG 2 on food security depends on cultivating shade-tolerant crops such as lettuce and spinach (Priscilla et al., 2024). According to the research conducted by Adeh et al. (2019), the aim of SDG 13 is to reduce greenhouse gas emissions, which is achieved through climate action. Sustainable Development Goal 11 will, as it is evident since Walston et al. (2022) state, be boosted due to sustainable land use and community livelihood, whereas Sustainable Development Goal 15 will be elevated in terms of less land clearance to support terrestrial ecosystems. Table 3 presents the key contributions of agrivoltaics systems to achieving the SDGs.

Table 3. SDG Contributions in agrivoltaics

SDG	Contribution	Measurable Data	Reference for Measurable Data
SDG 7 (Affordable and Clean Energy)	Cleans green energy, increasing access to clean energy.	India: 15.9 per cent of the entire producing capacity with solar (2023); nearly 85 GW accomplished by December 2024, and a goal of 100 GW by 2022.	MNRE. (2024); Kumar et al., 2020
SDG 2 (Zero Hunger)	Improves food security by keeping farms under agricultural production under solar panels.	Land equivalent ratios (LER) range from 1.67 to 1.93; in some situations, they result in up to a 100 per cent increase in shade-tolerant crops (cherry, tomatoes).	Barron-Gafford et al. (2019); Ghosh (2023)
SDG 13 (Climate Action)	Minimises GHG emissions from renewable energy sources, reducing the effects of climate change.	The capability to outweigh the use of carbon-based energy, which would transform 1 per cent of all global crop area, decreasing CO_2 emissions by 13 to 731 g/kWh compared to coal utilization.	Adeh et al. (2019); Shahsavari & Akbari (2018)
SDG 11 (Sustainable Cities and Communities)	Encourages steady land use and income diversity through electricity sales.	Through case studies (Sitapur, India), it is demonstrated that income increases through net metering; land values in particular areas increase by more than 30%.	Majumdar and Pasqualetti (2018); IISD. (2023)
SDG 15 (Life on Land)	Lightens the burden of land restoration and promotes soil protection by using dual-use systems.	An increase of 70-80 per cent in productivity of the land, with a maintenance of the use of land as agricultural land.	Jain et al. (2021)

AV systems and smallholder farmers in Sitapur, India – a successful case study

The case study has focused on a small town in the state of Uttar Pradesh, namely Sitapur (27° 34′ 0″ N; 80° 41′ 0″ E) (Krishnan, 2022). The town's climate is humid subtropical, with dry winters. The area has been recording significant output losses, partly due to unfavourable rainfall patterns and harsh temperatures. Extreme weather conditions have not only affected farm productivity but also doubled food prices in the local area. Knowledge of an AV project undertaken by the Central Arid Zone Research Institute (CAZRI) led farmers in Sitapur to aspire to use AV as a possible means of solving several of their problems (Yadav, 2025). Other farmers in Sitapur cooperated with CAZRI in the construction of the mini AV system by using the savings they had on government subsidies in the countryside. The cost of power produced by a single wheat farmer was estimated to run three night lamps, and this was compared to three more wheat tillers per square meter in sections of the field where the AV systems were not installed. The small AV systems gave the farmers a feel of the value in the area. They, however, added that the scaling would be accompanied by additional funding and technology support, such as access to low-cost credit, knowledge and data exchange among AV systems in India to inform the management of new and existing installations more effectively. Use of AV systems has been on the rise in India, with the country being one of the pioneers of the Global South, and several experimental and some commercial-scale experiments are underway in irrigation and aquaculture. This growth has created the India Agrivoltaics Alliance (https://indiaagripv.org/) an organization that has united stakeholders within the value chain in the solar and agricultural sectors to coordinate the stakeholder inputs in the sector, supporting the agrivoltaics adopted within the sector in the country, and appropriate policy recommendations that can assist in developing a comprehensive policy framework that can support agrivoltaics (Priscilla et al., 2025). Additionally, Table 4 provides evidence that the organization supports the agrivoltaics system.

Table 4. Key organizations supporting agrivoltaics in India

Organization	Role in Agrivoltaics	Key Contributions	References
AiDO (Agrivoltaic Conference Network)	AV stakeholders network platform that provides a place to share knowledge and update on events.	Raises awareness, and engages policy advocacy through India Agrivoltaics Alliance.	India Agrivoltaics Alliance. https://indiaagripv.org/
Central Arid Zone Research Institute (CAZRI)	Carries out AV research on arid lands, under the Indian Ministry of Agriculture.	Puts into practice AV pilots in Rajasthan growing mungbean, chickpea and cumin; an inspiration to projects such as Sitapur.	IISD. (2023). Agrivoltaics in India. https://www.iisd.org/publications/report/agrivoltaics-in-india CAZRI. (2024). Research Programs. https://www.icar-cazri.res.in/
Indian Council of Agricultural Research (ICAR)	The supervisor of the agricultural research that deals with AV-related studies and education as an apex body.	Facilitates the work of the AV pilots by assisting them at institutes such as CAZRI and the Krishi Vigyan Kendras	https://www.icar.org.in/
Jain Irrigation Systems Ltd.	Offers supporting facilities of micro-irrigation and AV projects, especially to water-efficient systems.	Applying AV projects that increase the efficiency of water use.	Priscilla et al. (2024) https://www.jains.com/
Krishi Vigyan Kendra (KVK) Delhi	Farms tests and training of farmers in AV under ICAR and in horticulture.	Practices an elevated AV system of 10 kW in Delhi, where okra, tomato and brinjal are cultivated	Priscilla et al. (2024)
National Solar Energy Federation of India (NSEFI)	Solar energy proponents who parade as industry advocates and policy makers of AV.	Affects the policy framework such as PM-KUSUM to promote the AV adoption	NSEFI. (2024). Policy Advocacy. https://www.nsefi.in/
SunSeed APV Ltd.	Provides consultation and project management in AV, including design and implementation.	Favours AV project planning, but certain projects receive less documentation, indicating the need for case studies.	SunSeed APV. (2024). Services Overview. https://www.sunseedapv.com/
Central Institute of Horticulture, Nagaland	AV research under ICAR: works on PV systems in greenhouses.	Operates as an pilot project in Nagaland, having expanded lemon and sweet orange production to grow year-round.	Priscilla et al. (2024)

Prospects and way forward

The most effective solution to the numerous obstacles of implementing agrivoltaics is to establish collaborative efforts among all stakeholders. A coordinated effort in this direction can only be aided by the government, which can establish shared working groups comprising state officials, knowledge institutions, private developers, and farmer representatives. India's substantial solar energy potential necessitates the development of bespoke systems tailored to the Indian context. This initiative must be undertaken in collaboration between the central and state governments. It is incumbent upon individual states to offer incentives to establish the panels. The establishment of centres of excellence within higher education institutions, such as universities and technical colleges, is of paramount importance. Both the central and state governments must support these centres to facilitate capacity building by providing training programmes for farmers and private developers. Furthermore, the active involvement of farmers in adopting agrivoltaics is a pivotal element in integrating crop production with the implementation of renewable energy sources.

Conclusion

Agrivoltaics is an innovative solution to the multidimensional challenges of the food crisis, energy stability, and environmental sustainability, particularly in India, where land is scarce and energy demand is growing. Nonetheless, the high cost of installation, lack of exploitation of technology, and gaps in policies present barriers to large-scale adaptation. The counterargument, *i.e.*, the potential danger of soil compaction, and the absence of scientific research regarding the long-term outcomes on biodiversity and soil health, will have to be studied further. India will be well placed to lead the Global South in solar power, as it has high solar potential, particularly because it is more intense. To turn it into reality, AV must realise its potential in an orderly manner, among other ways, by introducing policy changes under schemes like PM-KUSUM, setting up centres of excellence to bolster capacities, and fostering multi-stakeholder cooperation, as seen in the initiatives of the India Agrivoltaics Alliance. The present paper provides practical recommendations to relocate agrivoltaics policy-making to policymakers, researchers, and practitioners, in a bid to foster a sustainable, mutually supportive partnership among food production, renewable energy, and ecosystem resiliency.

Author contributions

Rithiga Mohanraj: Writing – first draft; Govindaraj Kamalam Dinesh: Writing – first draft; review and editing, supervision; figures; Veluswamy Venkatramanan: review and editing; Rachana Dubey: review and editing; Rajan Bhatt: review and editing; Prakash Kumar Sarangi: review and editing; Mohan Packialakshmi: Figures; Nedumaran Sethupathi: Figures; Allimuthu Elangovan: Figures; Punabati Heisnam: Review and editing; Nath Karthika: First draft; Suresh Parvathy: First draft; Veerapandian Karthick: Review and editing

Acknowledgment

The authors would like to acknowledge their affiliated institutions for providing research facilities and access to literature through ONOS. The authors gratefully acknowledge and thank Pixabay, Flaticon, and Napkin for providing valuable resources that supported this work.

Funding

No funding.

Conflict of interest

The authors declare no conflict of interest. The manuscript has not been submitted for publication in any other journal.

Ethics approval

Not applicable.

AI tool declaration

During the preparation of this work, the author(s) used Grammarly and QuillBot to correct grammatical errors and improve readability, content flow, and language. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

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