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Agrivoltaics: Growing Crops Beneath Solar Panels

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Agrivoltaics, also known as agro-photovoltaics or dual-use farming, is an innovative land-use approach that combines agricultural production with solar photovoltaic (PV) energy generation on the same piece of land. As climate change, population growth, and energy insecurity continue to challenge global food systems, agrivoltaics has emerged as a sustainable solution capable of addressing food, water, and energy demands simultaneously. Unlike conventional solar farms that often replace agricultural land, agrivoltaic systems allow crops to grow beneath or between elevated solar panels, creating a mutually beneficial relationship between farming and renewable energy production. Recent technological advancements, including bifacial solar panels, smart tracking systems, Internet of Things (IoT)-based monitoring, and artificial intelligence (AI)-driven farm management, have significantly enhanced the efficiency and economic viability of agrivoltaic systems. Research conducted across Europe, Asia, North America, and Australia has demonstrated improvements in water-use efficiency, crop resilience during heatwaves, and increased land productivity. However, successful implementation depends on crop selection, climatic conditions, solar panel design, and effective management practices. This article explores recent developments, research methodologies, outcomes, and future prospects of agrivoltaics while highlighting its role in promoting sustainable agriculture, renewable energy adoption, and climate-resilient farming systems. Agrivoltaics represents a transformative pathway toward achieving global food security and clean energy goals.

Keywords: Agrivoltaics; Solar Photovoltaics; Sustainable Agriculture; Renewable Energy; Climate-Resilient Farming

Introduction

The increasing demand for food, renewable energy, and sustainable land management has intensified competition for limited agricultural land across the world. According to the Intergovernmental Panel on Climate Change (IPCC, 2023), climate change has accelerated the frequency of droughts, heatwaves, and erratic rainfall, placing unprecedented pressure on agricultural productivity. At the same time, governments worldwide are rapidly expanding solar energy infrastructure to meet carbon neutrality targets, often resulting in the conversion of fertile farmland into large-scale photovoltaic (PV) installations. Agrivoltaics has emerged as a promising solution to this land-use conflict by integrating crop cultivation and solar electricity generation within the same landscape (Fraunhofer Institute for Solar Energy Systems [ISE], 2024).

The concept of agrivoltaics was first proposed by Goetzberger and Zastrow in 1982, but it has gained significant momentum during the past decade due to technological innovations and growing environmental concerns (Goetzberger & Zastrow, 1982). Modern agrivoltaic systems use elevated solar panels, adjustable mounting structures, bifacial

photovoltaic modules, and intelligent sun-tracking mechanisms that optimize both sunlight availability for crops and electricity production. Recent studies indicate that certain crops—including lettuce, spinach, tomatoes, potatoes, berries, and leafy vegetables—benefit from partial shading because reduced heat stress decreases evapotranspiration and conserves soil moisture (Barron-Gafford et al., 2019).

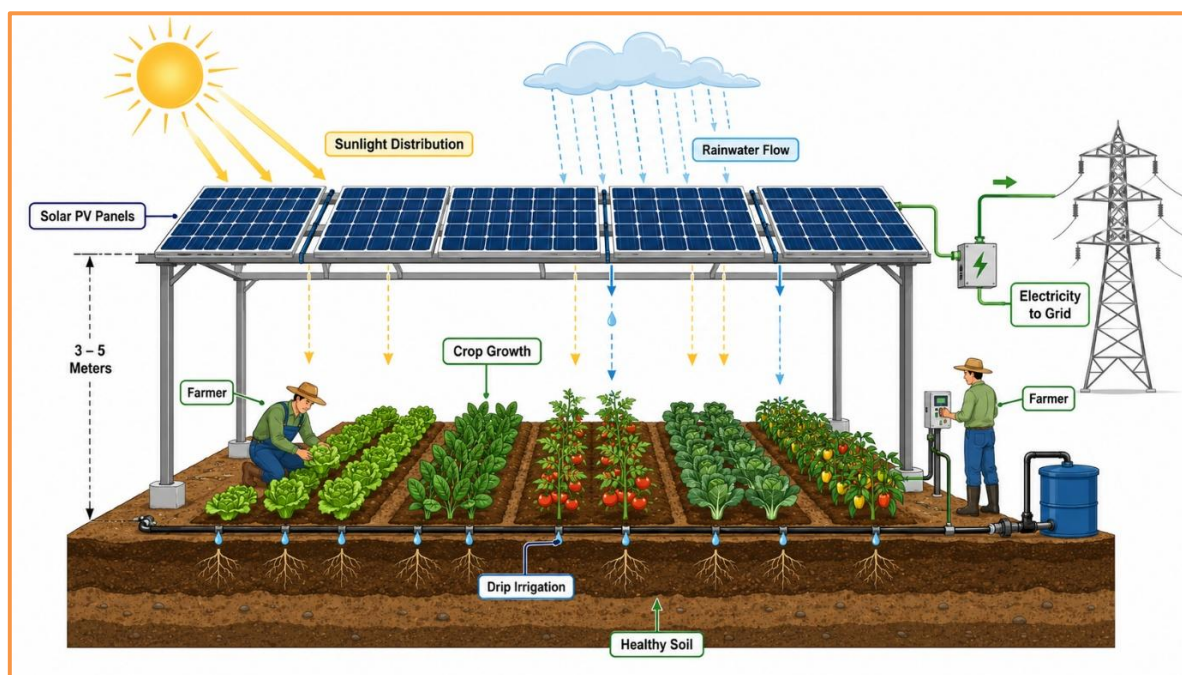


Figure 1. Conceptual illustration of an agrivoltaic system

Recent developments have further accelerated global adoption. Countries such as Germany, France, Japan, China, the United States, South Korea, and India are investing heavily in pilot projects that integrate renewable energy with precision agriculture. Artificial intelligence (AI), drone-assisted crop monitoring, remote sensing, and Internet of Things (IoT)-enabled irrigation systems are increasingly incorporated into agrivoltaic farms to maximize productivity while reducing operational costs. These advancements demonstrate that agrivoltaics is no longer merely an experimental concept but an emerging agricultural model capable of enhancing food security, improving farmer incomes, reducing greenhouse gas emissions, and supporting the United Nations Sustainable Development Goals (SDGs).

Methodology

The findings presented in this article are based on a comprehensive review of recent peer-reviewed research published between 2019 and 2025 on agrivoltaic systems, sustainable agriculture, and renewable energy integration. A narrative review methodology was adopted because it enables the synthesis of multidisciplinary evidence from agriculture, environmental science, engineering, and climate research. Scientific literature was gathered from reputable databases such as Scopus, Web of Science, SpringerLink, ScienceDirect, Wiley Online Library, and Google Scholar using keywords including *agrivoltaics*, *agrophotovoltaics*, *dual land use*, *solar farming*, *crop shading*, *photovoltaic agriculture*, and *renewable energy farming*.

The selected studies emphasized experimental field trials, comparative analyses, simulation-based investigations, and systematic reviews that evaluated the performance of agrivoltaic systems under different climatic conditions. Priority was given to research conducted in countries with well-established agrivoltaic projects, including Germany, France, Japan, the United States, China, South Korea, Italy, and India. Studies published in high-impact journals such as *Nature Sustainability*, *Applied Energy*, *Agricultural Systems*, *Renewable Energy*, *Solar Energy*, and *Journal of Cleaner Production* were considered to ensure the reliability and scientific credibility of the findings.

Table 1. Comparison between Conventional Farming and Agrivoltaic Farming

Parameter	Conventional Farming	Agrivoltaic Farming
Land use	Single purpose	Dual purpose
Energy generation	None	Solar electricity
Water consumption	High	Lower
Soil temperature	Higher	Reduced
Farmer income	Crop only	Crop + Electricity
Carbon emissions	Higher	Lower

Data extracted from the selected publications included crop yield, photovoltaic electricity generation, land equivalent ratio (LER), soil moisture retention, water-use efficiency, microclimatic conditions, carbon emission reduction, economic profitability, and farmer acceptance. Comparative evaluation methods were employed to examine differences between conventional agricultural systems, standalone photovoltaic farms, and integrated agrivoltaic systems.

Recent methodological advancements have also incorporated digital technologies into agrivoltaic research. Artificial intelligence algorithms are increasingly used to optimize panel orientation according to crop growth stages and weather forecasts. Internet of Things (IoT)-enabled sensors continuously monitor soil moisture, solar radiation, humidity, and temperature, allowing researchers to collect real-time environmental data. Drone-based multispectral imaging and satellite remote sensing provide detailed assessments of crop health, canopy development, and vegetation indices across large agrivoltaic fields. Machine learning models further assist in predicting crop performance and optimizing energy generation under varying climatic scenarios.

To enhance the validity of findings, results from different climatic zones were compared to identify consistent trends and region-specific outcomes. Although differences in crop species, solar panel configurations, and environmental conditions created some variability, the majority of studies consistently demonstrated improvements in land-use efficiency, water conservation, and renewable energy generation. This multidisciplinary methodology provides a comprehensive understanding of the opportunities and limitations of agrivoltaics while supporting evidence-based recommendations for policymakers, researchers, and agricultural practitioners seeking sustainable solutions for future food and energy systems.

Table 2. Selected International Case Studies Demonstrating the Adoption and Benefits of Agrivoltaic Systems

Case Study	Location	Project/Initiative	Key Features	Major Outcomes and Significance
Case Study 1	Germany	Fraunhofer ISE Agrivoltaic Project	• One of the earliest large-scale agrivoltaic experiments. • Elevated photovoltaic (PV) panels installed above agricultural crops. • Designed to enable simultaneous crop cultivation and solar electricity generation.	• Achieved over 60% improvement in land-use efficiency through dual land utilization. • Demonstrated that food production and renewable energy generation can coexist without significant compromise in crop yields. • Established a benchmark for agrivoltaic research and commercial deployment worldwide.

Case Study 2	Japan	Solar Sharing Farms	• More than 2,000 agrivoltaic farms operating across the country. • Cultivation of rice, vegetables, tea, and fruit crops beneath elevated PV structures. • Supported by favorable government policies and incentives.	• Increased farmers' income through dual revenue streams from agriculture and electricity sales. • Optimized land utilization while maintaining agricultural productivity. • Demonstrated the feasibility of integrating renewable energy with intensive farming systems.
Case Study 3	India	Pilot Projects in Gujarat and Maharashtra	• Demonstration projects established on dryland agricultural farms. • Integration of solar-powered irrigation with crop production. • Designed specifically for semi-arid climatic conditions.	• Improved irrigation reliability while reducing dependence on conventional energy sources. • Enhanced climate resilience and resource-use efficiency in water-scarce regions. • Contributed to India's renewable energy goals and promoted sustainable livelihoods for farmers.

Results and Discussion

The findings from recent agrivoltaic studies demonstrate that integrating solar photovoltaic (PV) systems with agricultural production offers significant environmental, economic, and social benefits. Unlike conventional land-use models where agriculture and solar energy compete for space, agrivoltaics enables the simultaneous production of food and clean electricity from the same land area. This dual-use approach has proven particularly valuable in regions facing land scarcity, water shortages, and rising temperatures (Barron-Gafford et al., 2019). One of the most notable outcomes is the improvement in **land-use efficiency**. Researchers commonly assess this using the **Land Equivalent Ratio (LER)**, which compares the productivity of combined land use with separate agricultural and energy systems. Numerous field experiments have reported LER values greater than 1.0, indicating that agrivoltaic systems produce more combined value than separate farming and solar installations occupying the same total land area (Dupraz et al., 2011). This finding suggests that agrivoltaics can significantly contribute to sustainable land management, particularly in countries where agricultural land is limited.

Crop performance under solar panels varies according to crop type, climate, and panel design. Shade-tolerant crops such as lettuce, spinach, kale, cabbage, broccoli, herbs, potatoes, strawberries, and tomatoes have shown stable or even improved yields under partial shading. Moderate shade reduces excessive solar radiation and heat stress, resulting in lower evapotranspiration rates and improved photosynthetic efficiency during hot weather (Barron-Gafford et al., 2019). Studies conducted in arid and semi-arid regions found that soil beneath solar panels retained higher moisture levels than open-field farms, reducing irrigation requirements and improving water-use efficiency. These advantages are increasingly important as climate change intensifies drought conditions across many agricultural regions (IPCC, 2023).

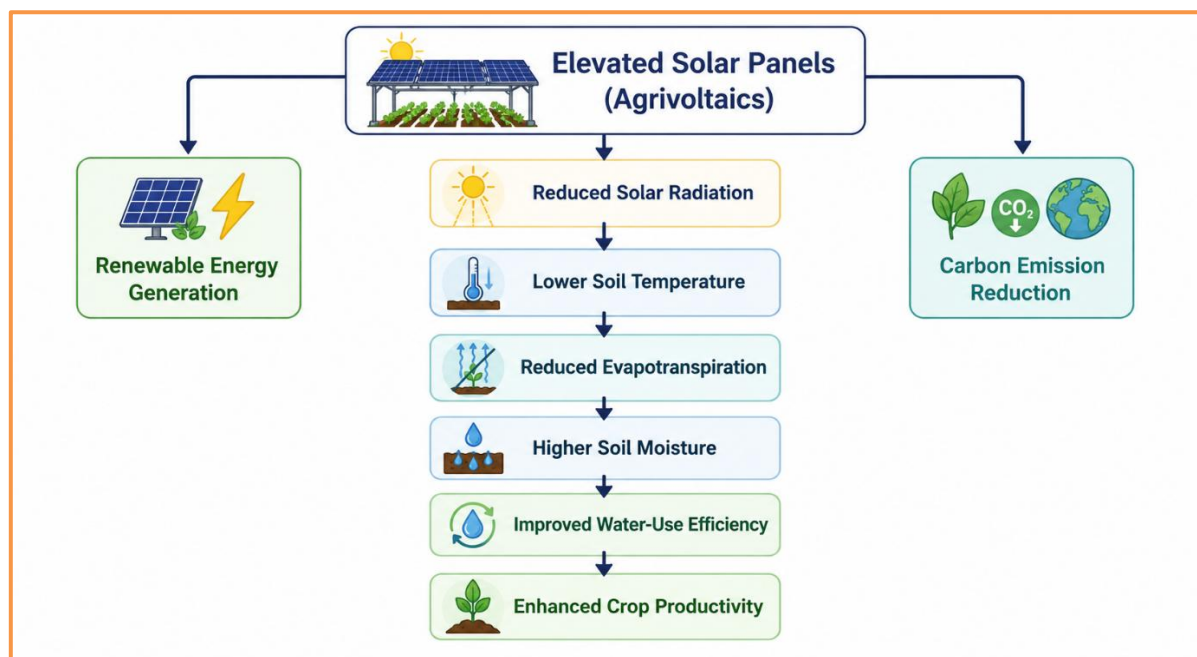


Figure 2. Effects of Agrivoltaics on Crop Growth and Environmental Parameters

Beyond crop production, agrivoltaics significantly enhances renewable energy generation. Elevated photovoltaic structures produce clean electricity that can power irrigation pumps, cold storage facilities, processing units, farm machinery, and rural households. Surplus electricity can also be supplied to national power grids, providing farmers with an additional and stable source of income. This diversification reduces dependence on unpredictable agricultural markets and strengthens rural livelihoods (Fraunhofer ISE, 2024).

Economic analyses consistently indicate that agrivoltaic systems improve long-term profitability despite higher initial installation costs. Although constructing elevated solar arrays requires greater investment than conventional ground-mounted panels, the combined income from electricity generation and crop production often offsets these costs within several years. Government subsidies, renewable energy incentives, and carbon-credit programs further improve financial feasibility in many countries. Consequently, agrivoltaics is increasingly viewed as an attractive investment for both private landowners and public institutions.

Technological innovation has played a crucial role in improving agrivoltaic performance. Modern systems employ **bifacial photovoltaic panels**, which capture sunlight from both the front and rear surfaces, increasing electricity generation. **Single-axis and dual-axis solar trackers** automatically adjust panel orientation throughout the day to optimize energy production while allowing sufficient sunlight to reach crops. Artificial intelligence (AI) and machine learning algorithms analyze weather forecasts, crop growth stages, and solar radiation to determine the most efficient panel positions. Simultaneously, Internet of Things (IoT)-based sensors continuously monitor soil moisture, temperature, humidity, and solar intensity, enabling precision irrigation and real-time farm management. Drone-based multispectral imaging further assists in identifying crop stress, nutrient deficiencies, and pest infestations before visible symptoms appear.

Table 3. Suitable Crops for Agrivoltaic Systems

Crop	Shade Tolerance	Reported Performance
Lettuce	High	Increased yield
Spinach	High	Improved quality
Tomato	Moderate	Stable yield
Potato	Moderate	Better water efficiency
Strawberry	High	Improved fruit quality
Herbs	High	Good adaptation

Environmental benefits extend beyond renewable energy generation. Agrivoltaic systems contribute to greenhouse gas mitigation by replacing fossil fuel-based electricity with solar power while maintaining agricultural productivity. Reduced soil temperatures beneath solar panels decrease water evaporation and help preserve soil organic matter. Furthermore, vegetation growing beneath panels suppresses dust accumulation, naturally cooling photovoltaic modules and improving their operational efficiency. Some projects have also incorporated flowering plants and pollinator habitats around solar installations, enhancing biodiversity and ecosystem services.

Despite these promising outcomes, several challenges remain. The performance of agrivoltaic systems depends heavily on appropriate crop selection, local climatic conditions, panel spacing, and structural design. Crops requiring full sunlight, such as maize and wheat in certain environments, may experience yield reductions under excessive shading. High installation costs, limited technical expertise, inadequate policy support, and regulatory uncertainties continue to restrict widespread adoption, particularly in developing countries. Standardized design guidelines and long-term economic assessments are still evolving, highlighting the need for continued interdisciplinary research.

Overall, the evidence strongly indicates that agrivoltaics offers a balanced solution to the interconnected challenges of food security, renewable energy production, climate resilience, and sustainable land management. Its ability to optimize land productivity while reducing environmental impacts positions it as one of the most promising innovations for climate-smart agriculture in the twenty-first century.

Future Perspectives

The future of agrivoltaics is closely linked to advances in renewable energy technologies, digital agriculture, and supportive public policies. As countries intensify efforts to achieve net-zero carbon emissions and strengthen food security, agrivoltaic systems are expected to become an increasingly important component of sustainable rural development. Future research will likely focus on crop-specific solar panel designs, adaptive shading technologies, transparent photovoltaic materials, and automated tracking systems capable of responding to changing weather conditions in real time.

Artificial intelligence, machine learning, robotics, and the Internet of Things (IoT) are expected to transform agrivoltaic management through predictive analytics, automated irrigation scheduling, precision fertilization, and continuous environmental monitoring. These technologies will enable farmers to maximize both agricultural productivity and energy generation while minimizing resource consumption.

Table 4. Advantages and Limitations of Agrivoltaics

Advantages	Limitations
Efficient land use	High capital investment
Renewable electricity	Complex design
Water conservation	Crop-specific suitability
Climate adaptation	Maintenance costs
Increased farmer income	Lack of awareness

Developing countries, including India, possess considerable potential for agrivoltaic expansion because of abundant solar radiation and extensive agricultural landscapes. However, widespread adoption will require supportive government policies, financial incentives, farmer training programs, and investments in rural infrastructure. Future interdisciplinary collaborations among agronomists, engineers, economists, environmental scientists, and policymakers will further improve system design and commercial viability. With continuous technological innovation and effective policy implementation, agrivoltaics has the potential to redefine sustainable land use by creating resilient farming systems that simultaneously address global challenges related to food production, clean energy generation, water conservation, and climate change adaptation.

Conclusion

Agrivoltaics represents one of the most promising innovations for addressing the interconnected challenges of food security, renewable energy generation, and sustainable land management. By integrating agricultural production with solar photovoltaic systems, this dual-use approach maximizes land productivity while minimizing competition between food production and clean energy development. The growing body of scientific evidence indicates that agrivoltaic systems can improve water-use efficiency, enhance soil moisture retention, reduce crop heat stress, generate renewable electricity, and diversify farmers' income sources. These advantages make agrivoltaics particularly valuable in regions experiencing climate change, water scarcity, and increasing pressure on agricultural land.

Recent technological advancements, including bifacial solar panels, automated tracking systems, artificial intelligence, Internet of Things (IoT)-based monitoring, drone-assisted crop surveillance, and precision agriculture, have significantly improved the efficiency and commercial viability of agrivoltaic systems. Research conducted across Europe, Asia, and North America demonstrates that carefully designed agrivoltaic installations can maintain or even increase crop productivity while simultaneously producing substantial quantities of clean electricity. However, successful implementation depends on appropriate crop selection, climatic suitability, optimized panel configuration, supportive government policies, and active participation from farming communities.

Despite challenges such as high initial investment costs, limited technical expertise, and evolving regulatory frameworks, agrivoltaics offers long-term economic, environmental, and social benefits. Continued investment in interdisciplinary research, farmer education, financial incentives, and demonstration projects will accelerate its adoption worldwide.

As nations strive to achieve the Sustainable Development Goals (SDGs) and net-zero carbon targets, agrivoltaics provides a practical pathway toward resilient agricultural systems that balance food production with renewable energy generation. By transforming agricultural landscapes into multifunctional ecosystems, agrivoltaics has the potential to shape a more sustainable, climate-resilient, and energy-secure future for generations to come.

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