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AGRIVOLTAIC SYSTEMS FOR SUSTAINABLE AGRICULTURE: WATER MANAGEMENT, CROP PRODUCTIVITY, FARM ECONOMICS, AND SMALLHOLDER ADOPTION IN INDIA - A COMPREHENSIVE REVIEW

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ABSTRACT
Agrivoltaic (APV) systems offer a sustainable solution to the increasing problems of food security, water scarcity, energy demand and climate change by merging agricultural production with photovoltaic electricity generation. This paper summarizes the present progress in agrivoltaic systems with a focus on water management, crop productivity, farm economics and smallholder uptake in India. Agrivoltaic systems achieve varying levels of crop productivity, depending on the environment, shading intensity, crop and system. In general, moderate shade improves crop yields and promotes the production of renewable energy. We study the economic potential of agrivoltaics using techno-economic indicators, land-use efficiency and income diversification, and governmental efforts to support its adoption such as PM-KUSUM. It also discusses issues such as large upfront costs, dispersed landholdings, lack of technical know-how, and crop-specific design specifications. The review concludes that agrivoltaic systems hold great promise for improving the relationship between food, energy, and water and for advancing resource-efficient, economically viable, and climate-resilient agriculture in India.
KEYWORDS: Crop productivity, water management, agrivoltaics and smallholder adoption

INTRODUCTION
Agriculture is key to global food security and rural livelihoods. However, competing demands for land, water and energy, and climate change pose challenges to feeding the future (Change, 2023; Nations, 2023). Droughts, floods, heat waves and erratic precipitation reduce agricultural productivity and increase production risk. But, the demand for food, freshwater and energy will increase significantly as the world's population is projected to reach 9.7 billion by 2050 (Change, 2023; D. et al., 2011; Nations, 2023; Nations, 2022). Agricultural land is shrinking at the same time under the pressure of industrialization, urbanization and the development of renewable energy (Randle-Boggis et al., 2025). Freshwater scarcity is particularly pronounced as rising temperatures increase evapotranspiration and crop water needs and agriculture accounts for around 70% of global freshwater withdrawals and directly competes with domestic and industrial demand (Change, 2023; Nations, 2023).The Water–Energy–Food (WEF) nexus is a key current framework for the integrated management of land, water and energy, responding to these interlinked pressures, as actions in one sector always affect the others (Allouche, 2024; Jain et al., 2023; Nations, 2023).
The rapid expansion of renewable energy, particularly solar photovoltaics (PV), is critical to global decarbonization. However, this land competition has intensified as conventional ground-mounted PV often occupies productive farmland, directly competing with food production for energy (Dinesh & Pearce, 2016; Dupraz et al., 2011; Weselek et al., 2021). Agrivoltaic (agri-photovoltaic) systems are the most popular dual land-use solution to this problem. Agrivoltaics was first proposed by Goetzberger and Zastrow (1982), who suggested elevating photovoltaic (PV) modules above agricultural crops to enable simultaneous crop cultivation and electricity generation. Since then, agrivoltaics has evolved into a climate-smart land-use strategy and has gained increasing attention across Europe, North America, and Asia because of its potential to improve land-use efficiency, enhance climate resilience, and support sustainable food–energy production (Dinesh & Pearce, 2016; Dupraz et al., 2011; Goetzberger & Zastrow, 1982; Gorjian et al., 2021; Weselek et al., 2021). Agrivoltaic systems enable the cohabitation of crop cultivation with

photovoltaic modules by optimizing panel height, row spacing, orientation and tracking configurations, which improves land-use efficiency while promoting renewable energy generation, agricultural sustainability and climate change mitigation(Amaducci et al., 2018; Dinesh & Pearce, 2016; Dupraz et al., 2011; Gorjian et al., 2021; Weselek et al., 2021).The agronomic argument hinges on the microclimatic impacts of agrivoltaics. A number of studies have demonstrated that partial shading of PV panels decreases air and soil temperature, wind speed and evapotranspiration and increases relative humidity (Adeh et al., 2018; Barron-Gafford et al., 2019; Dupraz et al., 2011; Elamri, 2011; Gorjian et al., 2021; Weselek et al., 2021). Lower temperatures in the canopy and soil reduce heat stress, increase photosynthesis, stomatal conductance, and water-use efficiency, and decrease soil evaporation, helping to maintain root-zone moisture during dry spells (Adeh et al., 2018; Barron-Gafford et al., 2019; Elamri, 2011; Marrou et al., 2013; Weselek et al., 2021). Agrivoltaics are a real climate-adaptation strategy, as irrigated agriculture faces increasing water shortages due to groundwater decline and climatic variability (Adeh et al., 2018; Barron-Gafford et al., 2019; Elamri, 2011; Gorjian et al., 2021; Marrou et al., 2013; Weselek et al., 2021) and studies have confirmed that well-spaced agrivoltaic systems reduce evapotranspiration and irrigation demand without excessive yield loss.

However, the response of crops to shading depends on the species: high shading can reduce biomass and yield in light-demanding crops, while moderate shading often increases productivity by reducing heat stress, especially for leafy vegetables, legumes, fodder and medicinal crops. For instance, soybeans and groundnuts show improved water-use efficiency under moderate shade (Barron-Gafford et al., 2019; Dupraz et al., 2011; Gorjian et al., 2021; Weselek et al., 2021). Thus, evaluation specific to crops is now required in place of optional (Dupraz et al., 2011; Weselek et al., 2021). The Land Equivalent Ratio (LER) is a widely used indicator of system performance; values greater than one suggest that the combined crop and electricity production from a shared parcel is higher than the production of separate mono-use land. Multiple field trials show LER values greater than unity (Adeh et al., 2018; Barron-Gafford et al., 2019; Dupraz et al., 2011; Weselek et al., 2021). Evapotranspiration and soil moisture under the panels cool PV modules, and since PV efficiency drops with temperature, the evaporative cooling actually increases electricity output – a mutually reinforcing relationship. This synergy adds further weight to the argument for the co-location of the two systems (Adeh et al., 2018; Barron-Gafford et al., 2019). The increasing convergence of IoT sensing, remote sensing and AI-based decision support is facilitating real-time irrigation scheduling and coordinated management of crop and energy output(Gorjian et al., 2021; Weselek et al., 2021).

India is a particularly promising site for agrivoltaic deployment given its vast agricultural acreage, robust solar irradiation (4–7 kWh $m^{-2}day^{-1}$), growing energy consumption and ambitious renewable targets (Agency, 2024; Energy, 2024; Nations, 2023). Government programmes like National Solar Mission and PM-KUSUM are supporting decentralised solar generation (including solar powered irrigation and grid-connected farm based PV) to reduce dependence on electricity for farmers and provide new sources of income (Energy, 2024; Jain et al., 2023). While this technology can offer income diversification and reduced irrigation costs, smallholder adoption is hampered by high capital costs, lack of technical expertise, fragmented landholdings and uncertainty over crop performance and long-term reliability (Adeh et al., 2018; Barron-Gafford et al., 2019; Development, 2024; Hassanpour Adeh et al., 2018; Nations, 2023; Weselek et al., 2021)

The global literature is growing quickly, but most field evidence is from Europe, North America, China and Japan. Long-term data on soil health, groundwater conservation, biodiversity, carbon sequestration and farm profitability, as well as standardized design guidelines for Indian panel height, spacing and tilt, are still missing, as are comprehensive studies conducted under Indian agroclimatic conditions and for major Indian crops like groundnut, pigeonpea, blackgram, greengram, cotton and oilseeds (Adeh et al., 2018; Dupraz et al., 2011; Elamri, 2011; Gorjian et al., 2021; Weselek et al., 2021).

This review synthesizes the state of knowledge on agrivoltaic systems for sustainable agriculture, with a focus on water management, crop productivity, farm economics, and smallholder adoption in India. We assess (i) microclimate modification, (ii) irrigation and soil moisture outcomes, (iii) crop growth and yield, (iv)Land-use efficiency, (v) energy generation, and (vi) economic performance. It further discusses the policy, technological and adoption barriers that will be the determinants of the successful scaling of agrivoltaics across Indian agriculture (Barron-Gafford et al., 2019; Gorjian et al., 2021; Weselek et al., 2021).

2. Evolution and Development of Agrivoltaic Systems

2.1 Origin and Concept of Agrivoltaic Systems

Agrivoltaic systems (AVS), also known as agri-photovoltaic (APV) systems, represent a new land-use strategy to produce agricultural crops and photovoltaic electricity on the same piece of land simultaneously (Dupraz et al., 2011; Goetzberger & Zastrow, 1982).The idea was born to meet the growing competition between food production and the

production of renewable energy, especially in areas with limited arable land and rapidly increasing energy needs (Goetzberger & Zastrow, 1982).
The basic principle of agrivoltaics is to optimize the spatial arrangement of photovoltaic modules in order to provide enough solar radiation to the crop canopy and to convert the remaining solar energy into electricity. Contrary to conventional ground-mounted solar farms that frequently use agricultural land, agrivoltaic systems enable farming to continue under or between solar panels leading to more efficient use of the land (Dupraz et al., 2011; Weselek et al., 2021). The major milestones in the evolution of agrivoltaic systems are summarized in Figure 1.

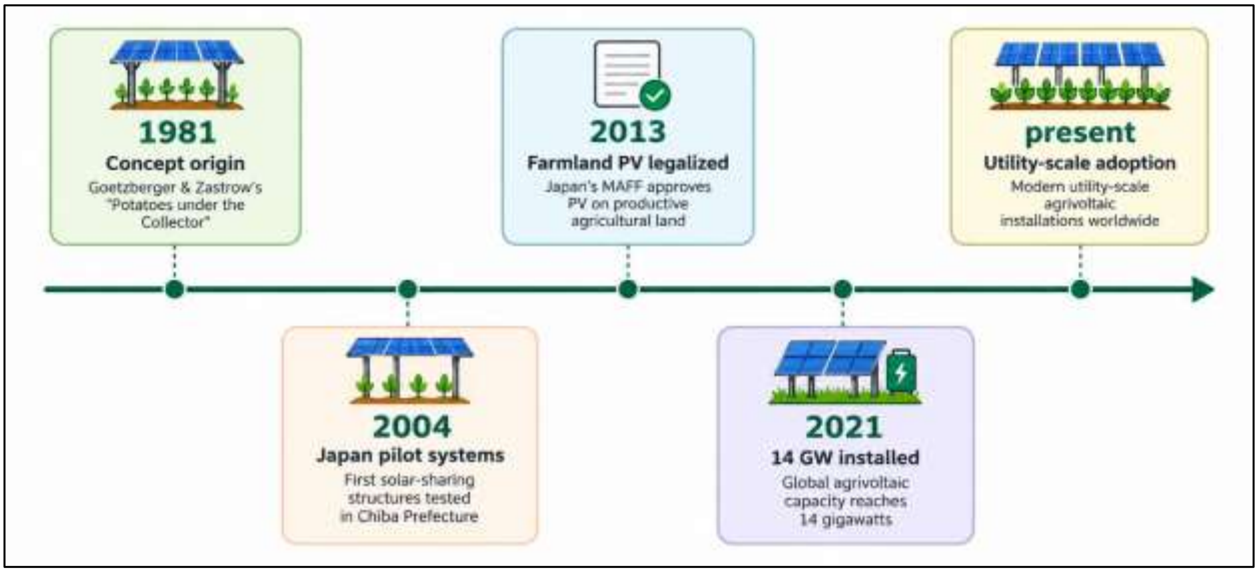

Figure 1.Historical evolution and major milestones in agrivoltaic system development from 1982 to the present

The concept of combining agriculture and solar energy became very popular after Dupraz et al. (2011) proposed the concept of maximizing Land Equivalent Ratio (LER) indicating that the combined production of food and energy can be more productive than the separate agricultural and photovoltaic installations. Since then, agrivoltaics has grown rapidly in response to increased concerns about climate change, land degradation, water scarcity and global food security (Barron-Gafford et al., 2019; Gorjian et al., 2021).
Agrivoltaics has become an integral part of climate-smart agriculture as it addresses three major global challenges of sustainable food production, renewable energy generation and efficient natural resource management simultaneously. Thus, agrivoltaic systems are increasingly seen as a relevant technological solution in the Food–Energy–Water (FEW) nexus framework (Nations, 2023; Weselek et al., 2021).

2.2 Historical Development of Agrivoltaic Systems

The idea of agrivoltaics has come a long way in the last 40 years. The idea of raising photovoltaic panels above agricultural land to allow for both crop cultivation and electricity generation was first suggested by Goetzberger and Zastrow in 1982 (Goetzberger & Zastrow, 1982). However, the practical application was still limited by the high costs of photovoltaic technology and the insufficient investigation of the compatibility with agriculture. In the early 2000s, the price of photovoltaic modules decreased and interest in renewable energy increased, leading to pilot-scale agrivoltaic projects in Europe and Japan. Researchers started to investigate crop responses to partial shading and economics of dual land-use systems (Marrou et al., 2013).
(Dupraz et al., 2011) made an important contribution by developing the first complete agronomic framework for agrivoltaic systems and showing that they can enhance the overall productivity of land, using the Land Equivalent Ratio concept. Their work laid the scientific foundation for future agrivoltaic research across the globe.
Agrivoltaic systems have grown rapidly in countries such as Germany, France, Italy, Japan, China, South Korea, the United States and others in the last ten years. Recent innovations are high photovoltaic structures, bifacial solar modules, single and dual axis tracking systems, semi-transparent photovoltaic panels and smart control systems that dynamically control shading according to the needs of the crop (Gorjian et al., 2021; Weselek et al., 2021).
Research on agrivoltaics in India has been gaining increasing attention, due to the country's vast solar resources, large agricultural land base and increasing focus on renewable energy. While interest in the integration of photovoltaic systems with agricultural production has increased with government schemes like PM-KUSUM, commercial adoption of agrivoltaic systems is still in its infancy(Energy, 2024).

2.3 Classification of Agrivoltaic Systems
The agrivoltaic systems can be categorized based on photovoltaic structure, panel orientation, mounting height and operational mechanism. Agrivoltaic systems can be classified into different configurations as illustrated in Figure 2.

2.3.1. Fixed-Tilt Agrivoltaic Systems
Fixed-tilt systems, the simplest and most common agrivoltaic configuration. The photovoltaic modules are mounted at a fixed tilt angle and remain fixed throughout the year. These systems have relatively low installation and maintenance costs and are suitable for field crops grown in conditions of moderate shading (Weselek et al., 2021). However, the lack of solar tracking could lower annual power generation compared with tracking systems.

2.3.2. Elevated Agrivoltaic Systems
Elevated agrivoltaic systems are photovoltaic systems that raise photovoltaic modules to heights of about 3 to 5 m or more above the ground. The raised clearance allows tractors, farm machinery and workers to carry out normal agricultural operations under the panels while minimizing shading intensity. Elevated systems are particularly suited to cereals, pulses, oilseeds, vegetables and horticultural crops that need mechanized cultivation (Dupraz et al., 2011).

2.3.3. Tracking System Monitoring
Agrivoltaic systems use single- or double-axis tracking mechanisms that continuously adjust the direction of the panels to maximize solar energy capture. The systems improve the efficiency of photovoltaic systems but are more expensive to install, need more maintenance, and are structurally more complex (Gorjian et al., 2021).

2.3.4. Vertical Agrivoltaic Systems
Vertical agrivoltaic systems are those in which photovoltaic panels are arranged vertically. This arrangement reduces shading of permanent crops and facilitates efficient use of diffuse solar radiation and agricultural operations. In regions with high solar radiation and mechanized agriculture, vertical systems are increasingly explored (Weselek et al., 2021).

2.3.5. Semi-transparent and Bifacial Agrivoltaic Systems
Recent technological advances have produced semi-transparent photovoltaic modules that allow a fraction of the incident solar radiation to reach the crops beneath the panels. Similarly, bifacial photovoltaic modules generate electricity from both the front and rear surfaces, increasing energy output with little increase in land usage. These technologies present promising opportunities for simultaneously optimizing crop growth and electricity generation (Gorjian et al., 2021). The characteristics of major agrivoltaic configurations are summarized in Table 1.

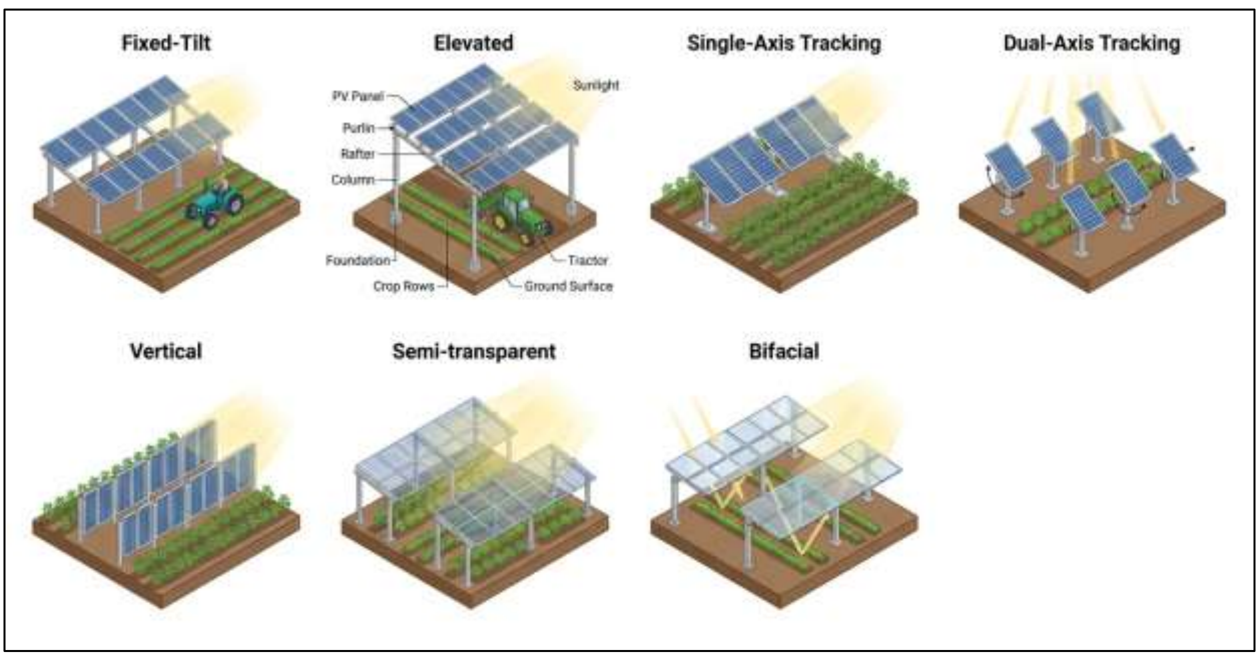

Figure 2 Classification of agrivoltaic systems based on structural configuration

Table 1. Comparison of different agrivoltaic system configurations

System type	Panel height	Advantages	Limitations	Suitable crops
Fixed-tilt	2–4 m	Simple, low cost	Fixed shading	Cereals, pulses

Elevated	3–5 m	Machinery access	Higher cost	Most field crops
Tracking	3–5 m	Higher energy yield	Complex, expensive	High-value crops
Vertical	2–3 m	Less shading	Lower direct irradiance capture	Row crops
Semi-transparent	Variable	Better light transmission	Higher module cost	Vegetables, horticultural crops
Bifacial	Variable	Increased energy output	Higher initial investment	Multiple crop systems

2.4 Major Components of Agrivoltaic Systems

An agrivoltaic system generally includes photovoltaic modules, mounting structures, support columns, foundations, electrical wiring, inverters, transformers, monitoring systems, and agricultural infrastructure. The incident solar radiation is then converted into electrical energy by photovoltaic modules. The panel is mechanically fixed and properly oriented by mounting structures made of galvanized steel or aluminum.

Automatic weather stations, soil moisture sensors, solar radiation sensors, temperature sensors, relative humidity sensors, wind speed sensors, and data loggers are becoming more common in modern agrivoltaic installations to continuously monitor the environmental conditions. These monitoring systems are employed for precision irrigation scheduling, crop management and photovoltaic performance assessment with real time data acquisition.

The operational efficiency of agrivoltaic systems has been greatly improved by the use of Internet of Things (IoT) technology, wireless sensor networks, artificial intelligence and cloud-based monitoring platforms. These technologies may be used for automated irrigation control, predictive maintenance of photovoltaic systems, and intelligent decision support for optimizing crop productivity and renewable energy generation (Gorjian et al., 2021).

3. Agrivoltaic Systems and Water Management

Water scarcity has become one of the major constraints to sustainable agricultural production worldwide threatening food security and economic development particularly in arid and semi-arid regions. Agriculture is the biggest user of freshwater resources, representing around 70% of global freshwater withdrawals (Nations, 2023). Growing populations, climate change, declining groundwater reserves, erratic rainfall patterns, and increasing competition among agricultural, domestic, and industrial sectors have placed significant pressure on global freshwater resources (Change, 2023; Nations, 2023).Groundwater provides almost two-thirds of the irrigation water in India. But continuous over-exploitation of groundwater has led to falling water tables in many farming regions, making it necessary to adopt water-efficient irrigation strategies and climate-resilient farming practices. Therefore, improving irrigation efficiency and increasing water productivity are major priorities for sustainable agricultural development.

Recently, agrivoltaic systems have gained considerable attention as an innovative approach to improving agricultural water management along with generating renewable electricity. However, unlike traditional photovoltaic installations, agrivoltaic systems create a modified microclimate beneath the photovoltaic panels by partial shading that alters the energy balance between the atmosphere, crop canopy, and soil surface (Barron-Gafford et al., 2019; Weselek et al., 2021).Several field experiments have shown reductions in incoming solar radiation, air temperature, soil temperature, wind speed and vapor pressure deficit, with increased relative humidity below photovoltaic arrays (Elamri, 2011; Marrou, 2013). Recent work suggests that soil temperatures under agrivoltaic systems can decrease by roughly 1–5 °C, and air temperatures have been observed to decrease by 0.5–3 °C and relative humidity increase by 5–15% depending on climatic conditions, crop type and photovoltaic configuration (Barron-Gafford et al., 2019; Elamri, 2011; Weselek et al., 2021).Such positive microclimatic changes help to relieve heat stress on crops and offer better growth conditions during times of high evaporative demand (Barron-Gafford et al., 2019).

Evapotranspiration is one of the main factors determining the crop water requirement and reduction in solar radiation reaching the soil surface plays a significant role in it. Partial shading reduces soil evaporation and lower temperatures in the canopy reduce transpiration rates, thus reducing overall evapotranspiration of the cropping system (Adeh et al., 2018; Barron-Gafford et al., 2019). Evapotranspiration reductions of 10% to 35% have been reported in recent experimental studies and systematic reviews for agrivoltaic systems compared to conventional open-field cultivation, but the magnitude of the reduction is dependent on shading intensity, crop species and climatic conditions (Adeh et al., 2018; Barron-Gafford et al., 2019; Gorjian et al., 2021; Weselek et al., 2021). The reduction of evapotranspiration permits crops to sustain a positive water status during dry periods and also results in more efficient use of available irrigation water (Adeh et al., 2018; Barron-Gafford et al., 2019).

Soil moisture conservation is another major benefit of agrivoltaic systems. Lower soil temperatures and reduced evaporation help to retain moisture in the crop root zone for longer periods, and therefore reduce the frequency of irrigation and improve drought resilience (Elamri, 2011; Marrou, 2013). Some studies have observed an increase in volumetric soil moisture content of approximately 10–30% under photovoltaic panels relative to nearby open-field conditions (Barron-Gafford et al., 2019; Weselek et al., 2021). Increased soil moisture enhances crop water availability, nutrient uptake, root growth, microbial activity and overall physiological performance particularly in water-limited environments (Barron-Gafford et al., 2019; Elamri, 2011) Therefore, agrivoltaic systems are being recognized as an effective way to increase agricultural resilience in the context of climate change(Weselek et al., 2021).

The modified microclimatic conditions beneath photovoltaic panels can substantially reduce crop irrigation requirements. Reduced evaporative demand, lower soil evaporation, and improved soil moisture retention enable crops to maintain growth with less frequent irrigation than under conventional open-field cultivation (Adeh et al., 2018; Barron-Gafford et al., 2019; Elamri, 2011).Recent studies indicate that irrigation water savings vary from 15% to 40% depending on the crop type, irrigation method, climatic conditions and agrivoltaic design (Gorjian et al., 2021; Weselek et al., 2021). However, the savings in irrigation are highly dependent on photovoltaic panel height, row spacing, tilt angle, orientation, shading percentage and crop characteristics(Dupraz et al., 2011; Weselek et al., 2021).Thus, a good optimization of these design parameters is essential to achieve the trade-off between electricity production, crop productivity and water saving, avoiding the excessive shading that can negatively affect photosynthesis (Dupraz et al., 2011; Gorjian et al., 2021).

The effectiveness of agrivoltaic systems is often assessed by water-use efficiency (WUE), which is commonly defined as the ratio of crop yield to water consumption. Enhanced soil moisture conservation with less evapotranspiration often leads to higher WUE without significant reduction in crop yield (Elamri, 2011; Weselek et al., 2021). Recent studies demonstrate that agrivoltaic systems can improve water-use efficiency by about 20-47%, especially in semi-arid environments where the crop production is limited by water availability (Barron-Gafford et al., 2019; Weselek et al., 2021). Better WUE improves sustainable management of groundwater, irrigation efficiency, and resilience of agricultural systems to prolonged drought periods (Gorjian et al., 2021; Nations, 2023). Figure 3 summarizes the influence of agrivoltaic systems on the microclimate and water management parameters. Reported water-saving performance of agrivoltaic systems in different crops is summarized in Table 2.

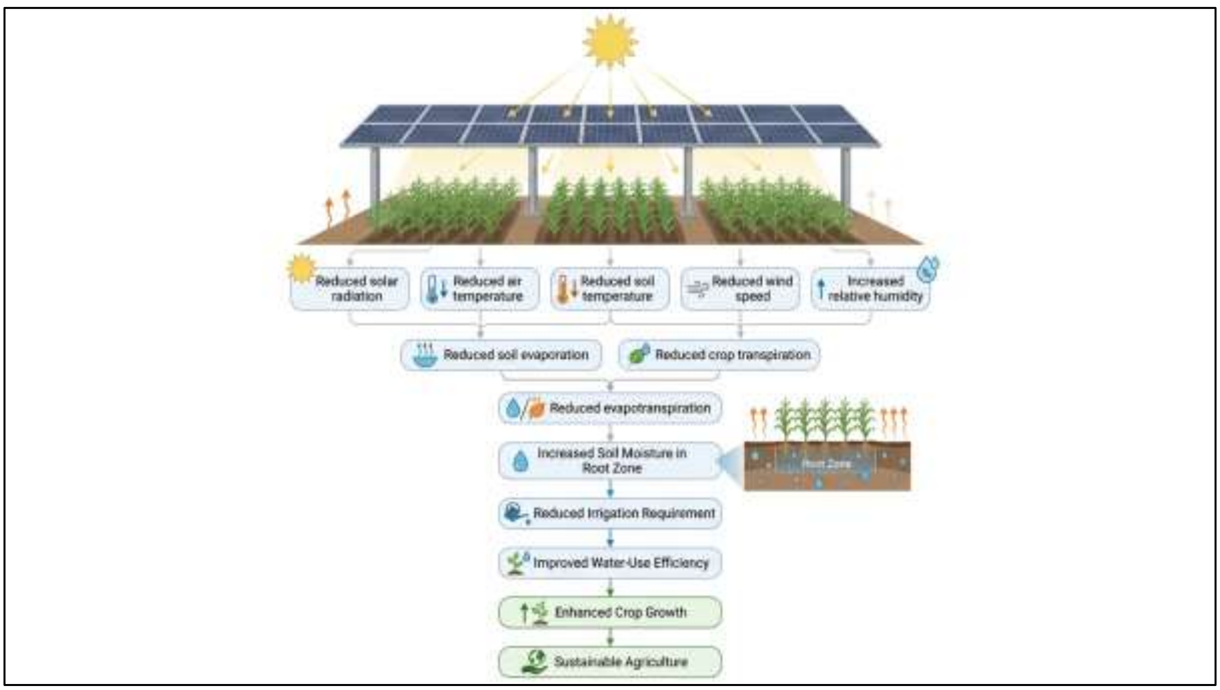

Figure 3 Effects of agrivoltaic systems on microclimate, soil moisture conservation, evapotranspiration, irrigation requirement, and water-use efficiency

Smart irrigation technologies have been integrated into agrivoltaic systems, enhancing water saving potential through recent advances in precision agriculture. Soil moisture sensors, automatic weather stations, wireless sensor networks, Internet of Things (IoT)-based communication platforms, cloud computing, and artificial intelligence (Gorjian et al., 2021) enable real-time monitoring of crop water status and environmental conditions. These technologies allow dynamic irrigation scheduling according to the real water needs of the crop, rather than fixed irrigation intervals, which reduces water losses and maintains the optimum soil moisture during the growing period of the crop (Gorjian et al., 2021). Artificial intelligence and machine learning algorithms are increasingly used to predict irrigation requirements by integrating meteorological data, soil moisture measurements and crop growth information, improving both water-use efficiency and operational decision-making (Gorjian et al., 2021).

Although there has been considerable progress in recent years, there are still some challenges concerning the optimization of water management in agrivoltaic systems. The water saving depends on the crop, climate and how the photovoltaics are installed, so crop-specific design recommendations and long-term field evaluations are needed (Gorjian et al., 2021; Weselek et al., 2021). Most of the studies have been conducted in Europe, North America, East Asia, while comprehensive investigation under diverse Indian agro-climatic conditions is limited (Weselek et al., 2021). Future research should focus on long-term assessment of groundwater conservation, root-zone water dynamics, crop-specific irrigation scheduling, and integration of AI-based irrigation management and development of standardized agrivoltaic design guidelines suitable for different climatic regions (Gorjian et al., 2021). This type of multidisciplinary research will facilitate the broader implementation of agrivoltaic systems to improve water security, agricultural resilience, and sustainable food–energy–water systems (Barron-Gafford et al., 2019; Weselek et al., 2021).

Table 2 Summary of water-saving performance of agrivoltaic systems in different crops

Crop	Country	Water saving (%)	Yield response
Lettuce	France	20–30	Increased
Tomato	USA	20–40	Increased
Pepper	USA	15–30	Increased
Wheat	Germany	10–20	Comparable
Soybean	Japan	15–25	Comparable

4. Agrivoltaic Systems and Crop Productivity

Crop productivity is one of the most important indicators for evaluating the performance of agrivoltaic systems, since these systems are designed to produce agricultural crops and renewable electricity simultaneously from the same land area (Barron-Gafford et al., 2019; Dupraz et al., 2011). Unlike conventional ground-based photovoltaic systems that usually displace agricultural land, agrivoltaics still keep crop farming but modify crop microclimate by partial shading. These changes affect crop growth, physiological processes, yield and quality, and therefore crop productivity is an important parameter to evaluate the sustainability of agrivoltaic systems(Weselek et al., 2021).

The response of crops to agrivoltaic systems is mainly dependent on the interaction of solar radiation, crop characteristics, climatic conditions and photovoltaic system design. Partial shading mitigates excessive solar radiation, lowers canopy and soil temperatures, increases relative humidity, and conserves soil moisture, thus creating favorable growing conditions especially in hot and semi-arid environments (Barron-Gafford et al., 2019; Marrou, 2013). Moderate shading conditions cause microclimatic alterations that reduce heat stress and improve plant physiological processes such as photosynthesis, stomatal conductance, chlorophyll retention, transpiration efficiency, and nutrient uptake (Adeh et al., 2018; Elamri, 2011). However, too much shading may reduce the photosynthetically active radiation (PAR) and thus reduce the biomass build-up and the yield of high-light-demanding crops. Thus, the optimization of panel height, spacing, orientation and shading intensity should be properly made to balance crop productivity with electricity production(Dupraz et al., 2011; Elamri, 2011).

Several studies have shown that agrivoltaic systems positively affect crop growth parameters such as plant height, leaf area index, chlorophyll content, biomass production, root development and dry matter accumulation (Barron-Gafford et al., 2019; Weselek et al., 2021). The environment with lower stress permits crops to maintain higher physiological activity under high temperature and low water availability. Improved soil moisture availability also enhances nutrient absorption and root growth, thereby contributing to better plant establishment and increased resilience under drought conditions (Elamri, 2011).

Crop response to agrivoltaic systems is highly variable between species, as it depends on shade tolerance, photosynthetic pathway, and canopy architecture and growth duration. Leafy vegetables, such as lettuce, spinach, and cabbage, are generally well suited to moderate shading as reduced solar radiation reduces heat stress and water loss while maintaining adequate photosynthetic activity (Barron-Gafford et al., 2019; Marrou, 2013). Fruit vegetables such as tomato and pepper have also shown stable or increased yields under agrivoltaic systems in water-limited environments due to improved microclimatic conditions(Barron-Gafford et al., 2019).Leguminous crops such as soybean, groundnut, pigeonpea and greengram could benefit from improved soil moisture conservation, but excessive shading may reduce pod development depending on the growth stage and configuration of the panel(Weselek et al., 2021).For cereals such as wheat and maize, careful optimization of shading intensity is usually necessary, as long-term reductions in solar radiation may limit grain filling and final yield(Dupraz et al., 2011). Reported water-saving potential and corresponding crop responses under agrivoltaic systems are presented in Table 3.

Table 3. Reported water-saving performance and crop yield responses under agrivoltaic systems in different countries

Crop	Country	Yield response	Shading level
Lettuce	France	Increased	Moderate
Tomato	USA	Increased	Moderate
Pepper	USA	Increased	Moderate
Wheat	Germany	Comparable	Low–Moderate
Soybean	Japan	Comparable	Moderate

Agrivoltaic systems can also impact crop quality in addition to crop yields. It has been reported that moderate shading enhances the nutritional quality, chlorophyll concentration, antioxidant content, vitamin composition, and marketable quality in several horticultural crops (Barron-Gafford et al., 2019; Marrou, 2013). Reduced thermal stress and improved water availability lead to better physiological stability and quality attributes, especially in vegetables and high value crops grown in warm seasons. However, the quality of the responses differs among crop species and environmental conditions, indicating the need for crop-specific management practices.

The Land Equivalent Ratio (LER) is one of the most common indicators used to evaluate the performance of agrivoltaic systems (Dupraz et al., 2011). It measures the productivity of food and electricity relative to the separate agricultural and photovoltaic production systems. An LER value greater than one indicates that the integrated system is more efficient in its land use than separate land uses. As illustrated in Figure 4, higher LER values demonstrate the superior land-use efficiency achieved through agrivoltaic systems. Many experimental studies have shown LER values between roughly 1.1 and 1.7, highlighting the potential of the agrivoltaic systems to increase the total land productivity while maintaining satisfactory agricultural and renewable energy yields (Gorjian et al., 2021; Weselek et al., 2021). This increased land use efficiency is particularly important in countries like India where growing food demand and renewable energy expansion compete for limited agricultural land.

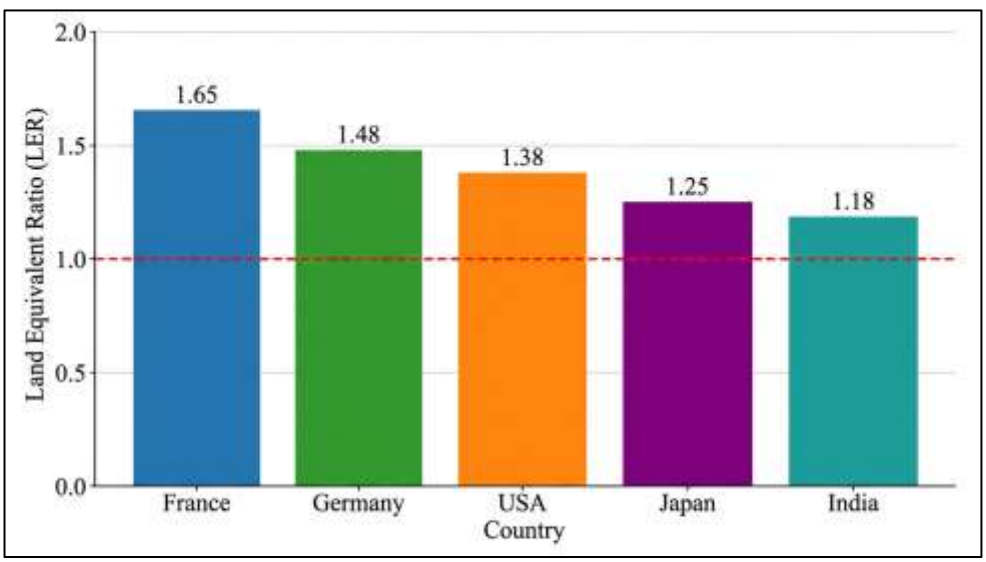

Figure 4 Comparison of reported Land Equivalent Ratio (LER) values for different agrivoltaic systems

Productivity of agrivoltaic systems is highly dependent on a number of design and environmental factors. Photovoltaic panel height influences machinery access and shading patterns, while row spacing and tilt angle affect the solar radiation received by the crop canopy (Dupraz et al., 2011). In addition, crop growth and yield are also affected by the panel orientation, tracking systems, seasonal solar angle, crop geometry, soil properties, irrigation management and the local climatic conditions(Gorjian et al., 2021).Thus, for maximum dual productivity of agriculture and energy, the design of agrivoltaic should be specific to the crops and regional environmental conditions.

Recent advances in precision agriculture have also enhanced crop management under agrivoltaic systems. Remote sensing, unmanned aerial vehicles (UAVs), Internet of Things (IoT)-based sensor networks, artificial intelligence, and machine learning algorithms allow continuous monitoring of crop growth, canopy temperature, soil moisture, chlorophyll status, and plant health (Gorjian et al., 2021). These technologies allow for precision irrigation, nutrient management, disease detection, and yield prediction, thus enhancing efficiency in resource use and overall crop

productivity. Hence, digital agriculture is expected to play an increasingly important role in the optimization of agrivoltaic farming systems under changing climatic conditions.
Despite substantial advances, important knowledge gaps remain on crop productivity under agrivoltaic systems. Most of the studies available have been on vegetables and horticultural crops whereas long term studies on cereals, pulses, oilseeds and forage crops are limited especially under tropical and subtropical environments. Further, optimum shading levels, panel configurations, crop selection and management practices are not standardized for different agro-climatic regions (Weselek et al., 2021). Future research therefore needs to concentrate on multi-location field experiments, crop-specific physiological studies, long-term productivity evaluation, and the integration of advanced digital technologies to optimize agricultural production while achieving efficient renewable energy generation. These studies will contribute to the development of resilient agrivoltaic systems that simultaneously improve food security, land use efficiency and climate adaptation.

5. Agrivoltaic Systems, Farm Economics, and Smallholder Adoption

The economic feasibility of agrivoltaic systems is a decisive factor for their large-scale implementation, particularly in developing countries where agriculture is the primary living source for rural communities. Agrivoltaic systems integrate photovoltaic electricity generation and agricultural production on the same land, providing double economic benefits that improve land productivity and diversify farm income compared with conventional farming or standalone photovoltaic installations (Barron-Gafford et al., 2019; Dupraz et al., 2011).This integrated approach reduces farmers' dependence on one source of income and improves resilience to crop failures, market price fluctuations and climate-induced production risks(Weselek et al., 2021)
Agrivoltaic systems are characterized by higher initial capital costs compared to traditional farming, but several techno-economic studies have shown that the long-term economic benefits outweigh the installation expenses. The primary capital costs are for PV modules, elevated support structures, electrical infrastructure, inverters, and installation, while operational and maintenance costs are relatively low over the 25- to 30-year service life of PV systems (Agostini et al., 2021; ISE, 2024). In techno-economic assessments, it has been shown that the revenues from electricity production, in addition to agricultural income, substantially enhance project profitability and shorten the investment recovery period under suitable policy support (Agostini et al., 2021).
A major economic benefit of agrivoltaic systems is the diversification of farm income. Farmers can earn income from crops and generate electricity for their own use or sell it to the grid through feed-in tariffs and net-metering (Change, 2023). This dual-income model improves financial stability and reduces the economic risks of uncertain weather conditions and volatile agricultural markets (Barron-Gafford et al., 2019). Moreover, agrivoltaic systems reduce the need for irrigation and groundwater pumping and decrease energy use, which in turn lowers production costs and increases net farm returns, especially in water-scarce regions (Adeh et al., 2018; Dupraz et al., 2011; Elamri, 2011; Weselek et al., 2021). The major economic benefits and challenges associated with agrivoltaic systems are summarized in Table 4.

Table 4. Economic benefits and challenges of agrivoltaic systems

Aspect	Benefits	Challenges
Farm income	Dual income from crops and electricity	High initial investment
Land use	Improved land-use efficiency	Site-specific design required
Water	Reduced irrigation cost	Initial infrastructure cost
Energy	Renewable electricity generation	Grid connectivity
Risk	Income diversification	Market uncertainty
Sustainability	Climate resilience	Technical knowledge requirement

The economic performance of agrivoltaic systems is usually assessed in terms of Net Present Value (NPV), Benefit–Cost Ratio (BCR), Internal Rate of Return (IRR), Payback Period, Levelized Cost of Electricity (LCOE) and Land Equivalent Ratio (LER). Of these, LER has emerged as one of the most accepted indicators because it quantifies the combined productivity of food and electricity generation from the same area of land. Many studies have reported LER values above one, which means that agrivoltaic systems are more land-efficient than separate agricultural and photovoltaic systems(Dupraz et al., 2011; Weselek et al., 2021). Similarly, techno-economic studies have demonstrated positive NPV, attractive IRR values, and shorter payback periods for favorable electricity prices, government incentives, and solar irradiation (Agostini et al., 2021; Feuerbacher et al., 2021).
Notwithstanding these advantages, adoption of smallholder farmers is still limited due to high initial investment cost, fragmented landholdings, limited access to institutional credit, and inadequate technical knowledge(Feuerbacher et al., 2021; Gorjian et al., 2021). Smallholders find it difficult to access affordable financing for photovoltaic infrastructure, so government intervention and innovative financing mechanisms are critical. The expansion of capital

subsidy programs, low-interest loans, concessional credit, green financing, and public-private partnership models can significantly reduce financial barriers and increase the affordability of agrivoltaic systems for resource-constrained farmers(Agency, 2023; Rahman et al., 2023).

Government policies are essential in promoting agrivoltaic adoption. India's Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan (PM-KUSUM) scheme has promoted decentralized solar power generation, solar-powered irrigation pumps, and grid-connected photovoltaic systems, providing opportunities to increase farmers' income while improving rural energy security(Energy, 2024). Recent studies suggest that expanding the PM-KUSUM scheme to explicitly support agrivoltaic systems through targeted capital subsidies, simplified approval procedures, appropriate feed-in tariffs, net-metering provisions, and dedicated financing mechanisms could substantially accelerate agrivoltaic adoption among Indian farmers(Energy, 2024; Ghamari et al., 2026).Further enhancing the economic feasibility of agrivoltaic farming would be policy integration with climate-smart agriculture, renewable energy, and water conservation programs. The economic benefits, adoption barriers, policy support mechanisms, and expected outcomes associated with agrivoltaic systems are summarized in Figure 5.

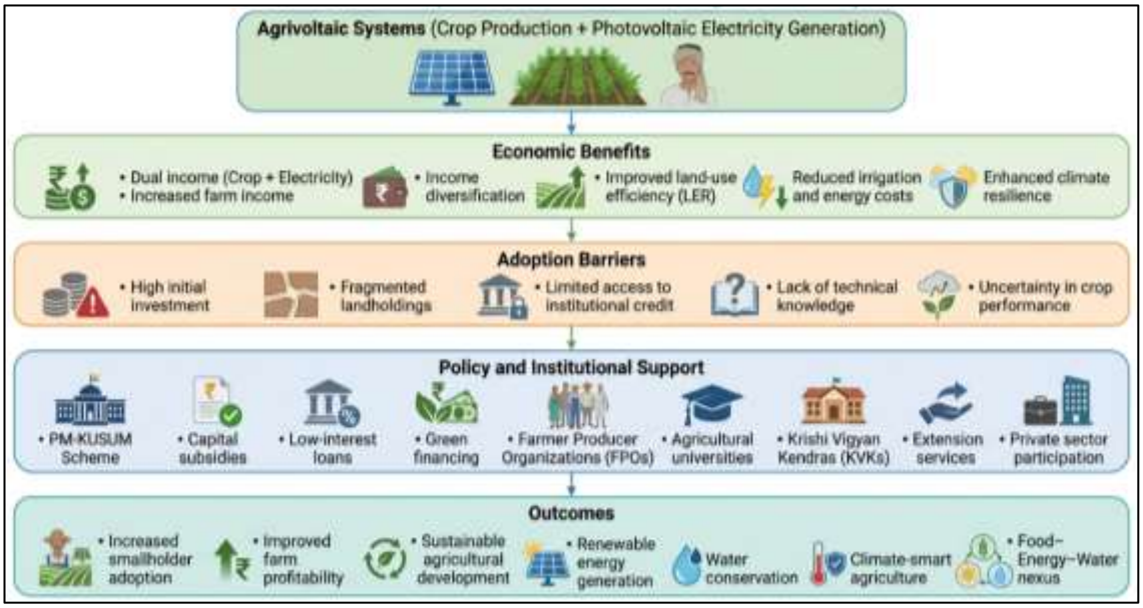

Figure 5 Economic and adoption framework of agrivoltaic systems

Farmer Producer Organizations (FPOs), agricultural cooperatives and community-based agrivoltaic projects represent promising institutional models for smallholder adoption. This reduces the financial burden on individual farmers and facilitates access to advanced technologies, maintenance services and electricity markets. Such collaborative approaches are particularly relevant in India, where average farm sizes are small and landholdings are fragmented. More recent adoption studies indicate that farmers' willingness to adopt agrivoltaic technologies is strongly influenced by awareness, access to reliable technical information, demonstration projects, perceived usefulness, and institutional support (Chamberlin et al., 2026; Wagner et al., 2024).

Capacity building and extension services are also important for successful implementation. The partnership between agricultural universities, Krishi Vigyan Kendras (KVKs), renewable energy agencies and private industries should create demonstration farms and training in system design, crop selection, photovoltaic maintenance, irrigation scheduling and digital monitoring technologies. Improved farmers' technical knowledge and confidence through field demonstrations and extension programs to speed up technology diffusion, particularly in regions where agrivoltaics are still relatively new.

Future economic studies should extend beyond traditional cost–benefit analysis by incorporating environmental and social benefits into holistic evaluation frameworks. Techno-economic models should be integrated with life-cycle cost assessment, carbon credit valuation, ecosystem service benefits, water conservation, greenhouse gas mitigation and climate resilience to allow for holistic assessment of agrivoltaic systems. Developing crop-specific economic models and financial strategies for different regions will help inform policy decisions and encourage smallholder farmers in India and other developing countries to adopt agrivoltaic systems at scale.

6. Challenges, Future Perspectives, and Policy Recommendations

Agrivoltaic systems are showing great potential to meet simultaneously the growing demand for food, renewable energy and water conservation. Major deployment of CDR has been hampered by technical, economic, institutional and policy-related challenges, despite great technological progress and successful pilot projects in some countries (Weselek et al., 2021; Gorjian et al., 2021). Breaking down these barriers is key to realizing the full potential of agrivoltaic systems as a sustainable land-use strategy.

One of the major technical challenges is the optimization of the design of photovoltaic systems for different crops and agro-climatic conditions. Parameters such as panel height, tilt angle, row spacing, orientation and shading intensity directly affect the crop growth, microclimate modification, electricity generation and water-use efficiency (Dupraz et al., 2011; Barron-Gafford et al., 2019). Moderate shading is beneficial for many crops, however, excess shading may reduce photosynthetically active radiation and adversely affect the productivity of light-demanding species. Hence, standards of design specific to certain crops and certain regions are needed to optimize agricultural as well as energy production.

Economic constraints remain a major obstacle especially for small scale farmers in developing countries. Adoption is still limited due to high initial investment costs, limited access to affordable financing, fragmented landholdings, and uncertainty about long-term economic returns(Feuerbacher et al., 2021).Improving the economic viability of agrivoltaic systems by providing access to broader capital subsidies, concessional loans, green financing, carbon credit schemes and public-private partnerships. Community-based ownership models like Farmer Producer Organizations (FPOs) and agricultural cooperatives can assist in further reducing the risks of investment while offering shared access to infrastructure and technical know-how.

Policy support will be crucial in accelerating agrivoltaics deployment. While initiatives like PM-KUSUM have encouraged solar-powered irrigation and decentralised renewable energy generation in India, specific policy frameworks for agrivoltaic systems are still missing (MNRE, 2024). Future policies should incorporate agrivoltaics into national strategies for renewable energy, sustainable agriculture, climate adaptation and water resource management. Financial incentives, reduction in procedures for approvals, feed-in tariffs, net-metering regulations, and standardized technical guidelines will promote private investment and increase technology adoption among farmers.

The fast development of digital agriculture is expected to further improve the performance of the agrivoltaic systems. The integration of artificial intelligence, Internet of Things (IoT)-based sensor networks, remote sensing, unmanned aerial vehicles (UAVs), robotics and decision-support systems can enable real-time monitoring of crop growth, soil moisture, photovoltaic performance and irrigation scheduling (Gorjian et al., 2021). These technologies will enable precision agriculture, optimize resource use, lower operating costs and increase the overall sustainability of agrivoltaic farming systems. The key challenges, technological innovations, future research priorities, policy interventions, and sustainable adoption pathway for agrivoltaic systems are illustrated in Figure 6.

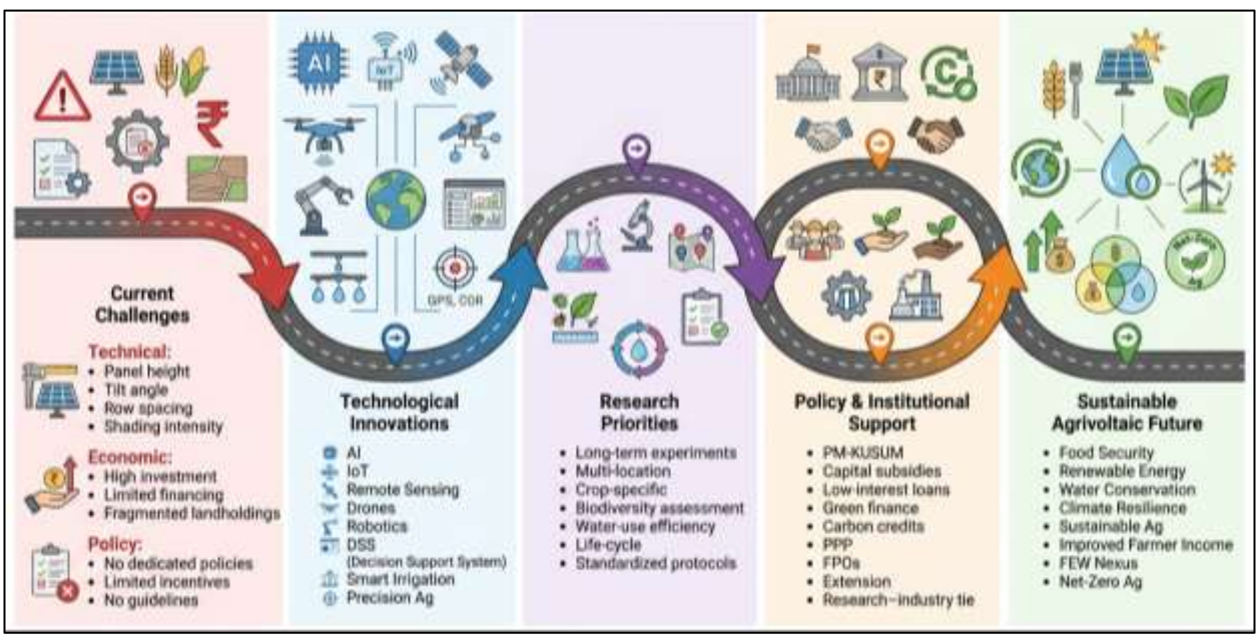

Figure 6 Roadmap illustrating the key challenges, technological innovations, future research priorities, policy interventions, and sustainable adoption pathway for large-scale agrivoltaic systems

Further research is required to address the knowledge gaps. Field experiments over the long term are required in different agro-climatic regions to evaluate crop productivity, soil health, biodiversity, water-use efficiency, photovoltaic performance and economic viability under different environmental conditions. Comparative studies on cereals, pulses, oilseeds, horticultural and fodder crops will help to understand crop-specific responses to partial shading. Create standard methods for evaluating land-use efficiency, environmental benefits, greenhouse gas mitigation, and life-cycle sustainability to facilitate meaningful comparisons across agrivoltaic systems worldwide.

For India, agrivoltaics is a promising way to tackle the interlinked challenges of food security, renewable energy generation, water scarcity and rural livelihood enhancement. We need coordinated work from government agencies, research institutions, industry, financial organizations and farming communities to succeed. To boost technology diffusion, stronger research–industry collaboration, demonstration farms, improved farmer training and extension services, and integration of agrivoltaics into national climate-smart agriculture initiatives are needed. With the necessary technological innovation, enabling policy frameworks and institutional cooperation, agrivoltaic systems can become an important part of sustainable agricultural development and greatly contribute to the achievement of national renewable energy, food security and climate resilience goals.

7. CONCLUSION

Agrivoltaic systems have shown great promise in facing issues related to water scarcity, food security, land use and management, and generation of renewable energy in an integrated manner. Agrivoltaics is the practice of producing solar electricity and growing crops on the same piece of land aiming to increase land use efficiency and create the ideal microclimatic conditions for resource conservation and growth. The literature review of the present study showed that agrivoltaic systems can improve crop resilience to climate change, reduce soil and air temperatures, conserve soil moisture, reduce evapotranspiration, and increase irrigation water use efficiency. These benefits are particularly important in areas of water deficit and semi-aridity where sustainable agricultural development is required.

The crop production of agrivoltaic systems is dependent on crop species, shading intensity, photovoltaic system structure and local environmental conditions. Moderate shading has been reported to improve physiological performance, reduce thermal stress and sustain acceptable yield, especially for shade-tolerant vegetables, horticultural crops and some leguminous crops (e.g. Experimental studies have shown that the use of agrivoltaic systems is more effective than separate systems for the production of food and energy on agricultural land, given that the combined production of crops and electricity results in a higher overall productivity of land with Land Equivalent Ratio values greater than unity.

Agrivoltaic systems that produce both renewable energy and agricultural products offer financial opportunities to diversify income. Lower energy use, more efficient resource use and less irrigation also make the farm more profitable in the long term. However, the high initial investment cost, lack of institutional funding, scattered landholdings and lack of technical know-how especially for smallholder farmers hinder widespread adoption. In India, government schemes such as PM-KUSUM, financial incentives, concessional finance, Farmer Producer Organizations (FPOs) and community-based ownership models can enhance the profitability and accessibility of agrivoltaic systems substantially.

The study also highlights the need for technological innovations such as precision agriculture, Internet of Things (IoT)-based monitoring, artificial intelligence, remote sensing, and smart irrigation systems to optimize agricultural and photovoltaic performance. These technologies can assist in expanding climate-smart agriculture by enhancing crop monitoring, scheduling irrigation, managing energy, and improving the overall efficiency of the system. Yet despite the progress made in agrivoltaic research, many questions remain open. Long-term multi-location field experiments, crop-specific design optimization, in-depth techno-economic assessment, life-cycle sustainability analysis, and standardized evaluation processes are still needed to foster evidence-based decision-making. Future studies should focus on designing region-specific agrivoltaic systems for different agroclimatic conditions, especially in developing countries where agriculture, water resources and renewable energy are closely intertwined.

Overall, agrivoltaic systems provide a new way to approach sustainable agriculture that can simultaneously increase food production, produce clean electricity, save water, and increase farm income. Technological innovation, supportive government policies, appropriate funding structures and efficient stakeholder collaboration can assist India and the rest of the world to capitalize on the potential of agrivoltaics to strengthen the food-energy-water nexus and create climate-resilient agricultural systems.

Declaration on the Use of Generative AI

During the preparation of this manuscript, the authors used QuillBot to improve the language, grammar, and readability of the manuscript.

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