



Review

Survey of Key Technological Innovations in Advanced Solar Panel Designs for Agro-Photovoltaic Systems

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Abstract

This paper provides a detailed overview of important technological innovations in agro-photovoltaic (Agro-PV) system design. This field combines solar energy generation with agricultural land use for producing both food and clean energy. Agro-PV systems tackle significant issues like land shortage, climate change, and the connection between food, energy, and water. They improve how land is used and boost sustainability. The survey looks at basic principles of Agro-PV, which include dual land use, how solar panels interact with crops, and different system setups such as fixed-tilt, tracking, vertical, and greenhouse-integrated PV structures. The paper explores key innovations such as bifacial solar modules, spectral splitting technology, adjustable-height and tiltable PV panels, smart water-harvesting panels, modular lightweight structures, and digital integration with IoT and artificial intelligence (AI). Bifacial panels increase energy output by capturing light on both sides, enhancing electricity production by 5 to 30% without hurting crop growth. Spectral splitting technology focuses photosynthetically active radiation (PAR) towards crops while directing other wavelengths to PV cells. This approach can lead to up to 39% greater efficiency and improves crop productivity. Adjustable-height and tiltable panels optimize sunlight exposure and shading, accommodating different crops and enhancing operational flexibility. Smart water-harvesting systems capture rainwater from panel runoff for irrigation and cleaning, improving water efficiency and system sustainability. Modular lightweight designs make installation easier, reduce stress on crops, and allow for simple scaling. Using AI-enabled sensor networks supports precision agriculture by optimizing resources and system performance in real time. The analysis shows that combining these technologies based on specific local climate and agricultural conditions leads to the best results for energy production and crop health. Nevertheless, challenges exist, such as high initial costs, complex systems, regulatory hurdles, and the need for careful crop selection for agro-voltaics. The survey points out gaps in research, especially in long-term field trials, crop compatibility, and integrated system optimization. The paper concludes that, agro-photovoltaic technological innovations have great potential for sustainable food and energy production. Customized deployment that includes bifacial and spectral splitting panels, adaptable structures, and smart management systems can significantly promote climate-resilient agriculture and renewable energy generation. Ongoing interdisciplinary research and supportive policy development are crucial to overcoming obstacles and fully realizing the benefits of Agro-PV systems worldwide..

Keywords: agro-photovoltaics, bifacial solar panels, spectral splitting, dynamic solar tracking, IoT smart sensors.

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1. Introduction

Agro-photovoltaic (Agro-PV) systems are an emerging interdisciplinary innovation at the interface of renewable energy generation and agricultural land use. The convergence of growing global challenges including climate change, rapid population growth, food insecurity, and pressing land scarcity has spurred scientific and industrial interest in maximizing the productivity and resilience of arable land. Agro-photovoltaics offer a unique, win-win solution by integrating solar photovoltaic (PV) installations with active crop production, allowing farmers to harvest both electricity and food from the same parcel of land.

Traditional agricultural methods and centralized energy production models increasingly compete for limited land resources. At the same time, the urgency of decarbonizing energy systems and ensuring long-term food supply presses for novel approaches to resource efficiency. Agro-PV systems directly address this land-use “food-energy” competition by enabling dual land utilization, effectively multiplying the portfolio of ecosystem services extracted from a given space. Recent advances in panel design, system configuration, and digital integration including adjustable-height and tiltable solar arrays, bifacial and spectral splitting panels, dynamic tracking, and IoT-enabled resource management have greatly improved both agronomic and energy outcomes in pilot and commercial-scale ventures. These innovations not only enhance land productivity but also foster rural electrification, microclimate stability, and water use efficiency, making Agro-PV particularly relevant for regions vulnerable to extreme weather and limited infrastructure.

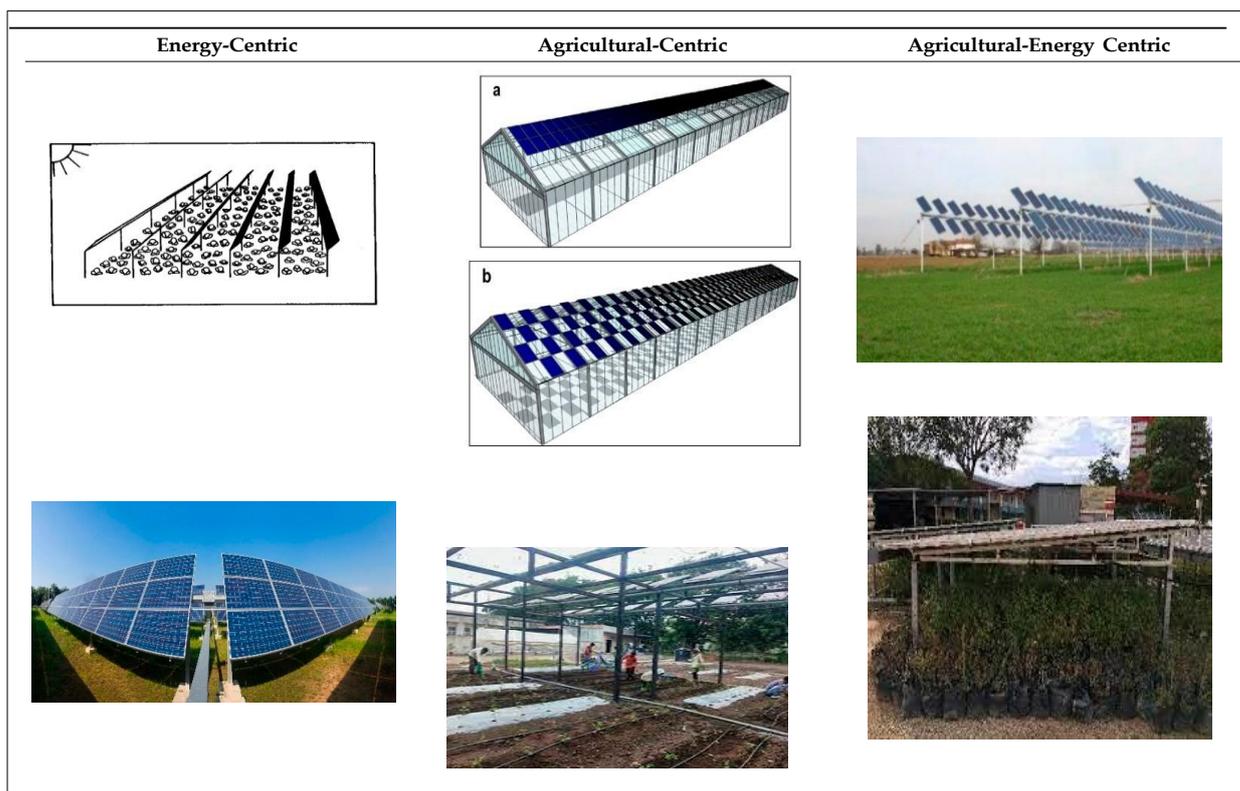


Figure 1: Approaches of agrivoltaic system (Mohd Ashraf, et al., 2021)

The fundamental principle of Agro-PV is dual land use, where land serves both as farmland and a solar power generator. Solar panels convert sunlight into electricity through the photovoltaic effect, wherein semiconductor materials absorb photons to generate direct current electricity. The integration with agriculture requires careful consideration of crop-light interaction, as natural sunlight is partially obstructed by solar panels. Crops rely on photosynthetically active radiation (PAR), primarily within the blue and red wavelengths (400-500 nm and 600-700 nm), to drive photosynthesis for biomass production. The design of Agro-PV systems aims to balance shading and sunlight

availability—ensuring crops receive adequate PAR while harvesting excess solar spectrum for electricity. This balance improves microclimate by reducing heat stress and conserving soil moisture (Azocleantech, 2025). Several configurations exist, each with advantages tailored to specific crops, climates, and land conditions. Some types of Agro-PV configurations possible are: Fixed-Tilt systems: fixed panels are installed at a determined tilt angle oriented to maximize annual solar exposure. These systems are simpler and less costly but offer limited adaptability to changing sun angles or crop phases. Fixed arrays typically maintain a balance between shading and energy generation by adjusting panel height and spacing (PMC, 2024). In dynamic solar tracking systems, panels are mounted on single- or dual-axis trackers that adjust orientation and tilt to follow the sun’s path. This maximizes electricity yield and can dynamically modulate shading for crops beneath using AI algorithms to optimize plant light needs and energy production simultaneously (Azocleantech, 2025). In vertical PV arrays, vertically oriented solar panels, often arranged in rows facing east-west, maximize agronomic space by reducing ground footprint. Bifacial vertical panels capture sunlight on both sides, increasing energy output while allowing enhanced sunlight penetration early and late in the day, benefiting shade-tolerant crops (Next2Sun, 2025). And in Greenhouse-Integrated PV Systems, solar panels are integrated into greenhouse roofs or walls, permitting controlled shading alongside electricity generation. These systems enhance crop environments while using available surfaces efficiently but require specialized PV modules suited for partial shading and diffuse light operation (TSE Energy, 2025).

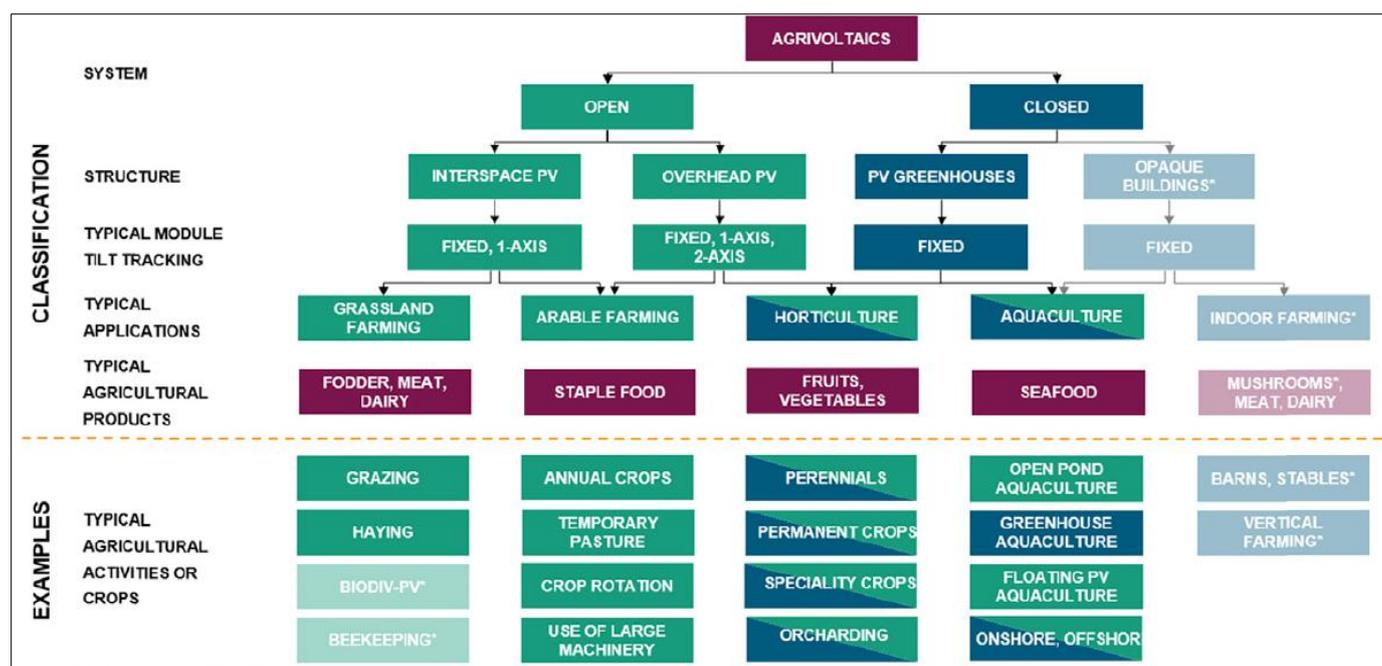


Figure 2: Classification of PV and agricultural colocation approaches (Gorjian S, et al., 2021).

This survey paper aims to systematically review, categorize, and compare the key technological innovations that define the current state and future trajectory of agro-photovoltaic system design. The analysis focuses on: Core design principles and technological advances (panel orientation, spectral management, dynamic shading); Structural and configuration innovations (vertical, inter-space, movable arrays, greenhouse-integrated PV); Digitalization and smart system management (IoT, AI, precision agriculture); Water management and resource efficiency (rainwater harvesting, shade-induced conservation); The review synthesizes findings from recent literature and leading pilot projects (2018–2025), drawing insights from both peer-reviewed studies and industry reports. This paper delivers several distinctive contributions such as, providing a comprehensive, up-to-

date synthesis of technological innovations underpinning modern Agro-PV systems. Detailing the performance trade-offs and complementarities among different system designs, considering energy yield, crop output, water efficiency, and economic returns. Highlighting regional and crop-specific implications, reflection of field-tested, context-dependent solutions. Discussing research gaps, challenges, and future directions for large-scale, sustainable Agro-PV deployment in diverse climates and farm typologies. Offering practical insights and technical comparisons of innovation trends (e.g., bifacial vs. spectral splitting panels, tracking vs. fixed tilt, vertical vs. interspace) for researchers, practitioners, and policymakers.

The paper is organized as follows: the introduction section presents background, motivation, scope, and structure. Section two which is the methodology of literature survey gives the details the systematic search, inclusion/exclusion criteria, and analytical methods. Section three, the background and fundamentals explain agro-pv principles, dual land use, panel-crop interactions, and basic system types. Section four, the key technological innovations provide the systematic survey of advances in structural design, energy-crop optimization, water management, and smart digital control in agro-pv design. Section five, the comparative analysis examines the differences across systems in terms of productivity, economics, climate suitability, and implementation challenges. While section six discuss on the challenges and research gaps that address the technical, socio-economic, and environmental hurdles. And the last two sections address future trends, research opportunities, and conclusion

2. Methodology of Literature Survey

The methodology of literature survey is structured to ensure a comprehensive, systematic, and robust collection and analysis of relevant academic and industry sources. It primarily draws from detailed practices observed in recent agro-photovoltaic research literature, including studies on lettuce agrivoltaics (Jamil, 2021) and a systematic review of agrivoltaics potential in Turkey using PVsyst simulations (Coşgun et al., 2024). The literature search was conducted across multiple established scientific and technical databases to capture the broad state-of-the-art in Agro-PV systems, ensuring both depth and breadth of coverage. Databases, such as Web of Science and Scopus were the primary databases for peer-reviewed journal articles and conference proceedings, favored for their comprehensive holdings and advanced search capabilities. Google Scholar was used for broader academic dissemination coverage, including theses and reports. Specialized platforms such as PubMed Central (PMC) and ScienceDirect that provided specific technical papers in agriculture, renewable energy, and sustainability domains. The search strategy combined key words and phrases relating to agro-photovoltaics and solar panel technologies. Searches were limited primarily to the most recent and relevant decade (2018–2025) to focus on current innovations and trends, while seminal earlier works were considered for foundational context.

The literature selection followed clear inclusion and exclusion criteria to prioritize quality and relevance. From the selected corpus, data were systematically extracted to address: the technical principles (e.g., spectral characteristics and solar irradiance management); system configurations (fixed tilt, tracking, vertical, greenhouse-integrated); crop growth impacts and light requirements; energy yield and land-use efficiency metrics; economic evaluations (cost-benefit, scalability); environmental and microclimate measurements; and innovations in water harvesting and IoT-enabled resource management. The extracted information was organized into thematic groups, enabling a structured survey of technological innovations with comparative insights. The survey applied qualitative content analysis to summarize and synthesize the literature comprehensively, supported by quantitative performance indicators reported across studies (e.g., Land Equivalent Ratio (LER), photosynthetically active radiation (PAR) metrics, energy efficiency percentages). Cross-validation of findings was done by comparing multiple studies assessing similar technologies (e.g., spectral splitting efficiency in Jamil, 2021 versus modeling in Coşgun et al., 2024).

3. Key Technological Innovations in Agro-Photovoltaic System Design

3.1. Adjustable-Height and Tilttable PV Panels

Key technological innovations in agro-photovoltaic (Agro-PV) system design involving Adjustable-Height and Tilttable PV Panels play a crucial role in optimizing the dual use of land for both efficient solar energy generation and productive crop growth. These innovations address the challenge of balancing light availability for crops with maximizing electricity output.

3.1.1. Adjustable-Height: Elevating solar panels above the ground, typically between 2 to 6 meters, allows sufficient space for agricultural activities such as planting, harvesting, and machinery operation beneath the panels. Adjustable height enables: Flexible shading control: Higher panels permit more light penetration to crops, which reduces excessive shading that could impair photosynthesis. Increasing height improves light distribution and microclimate conditions for crops (e.g., mitigating heat stress, conserving soil moisture). Crop-specific customization: Different crops require varying light intensities, which can be accommodated by adjusting the panel height. Improved land productivity: Elevated panels facilitate simultaneous farming under solar arrays, enhancing land-use efficiency without compromising either crop yield or energy generation. For example, systems with panels mounted at around 3 to 4 meters show increased sunlight beneath arrays, better microclimate regulation, and compatibility with farm machinery (Santra et al., 2025; Maysun Solar, 2024).

3.1.2. Tilttable PV Panels: Solar panels mounted on tilttable structures allow the angle of the panels to be adjusted seasonally or dynamically, enabling increase in solar irradiance on panels, maximizing electricity production. Secondly, by adjusting the tilt, the amount and pattern of shading on crops can be modulated, protecting crops from excessive solar radiation or heat stress while ensuring adequate photosynthesis, and also, part of single or dual-axis tracking systems that automatically follow the sun, further improving energy efficiency and balancing crop light needs (Leadvent Group, 2024). The synergy of adjustable height and tilt enhances energy generation efficiency by maximizing solar exposure throughout the year. Secondly, ensure agricultural productivity through light management and microclimate control, and finally, it enhance operational feasibility allowing farm equipment access and flexible crop management.

3.2. Bifacial Solar Modules

Bifacial solar modules represent a significant technological innovation in agro-photovoltaic (Agro-PV) system design, offering dual-sided sunlight capture to maximize energy generation while supporting agricultural production beneath. Unlike traditional monofacial solar panels that only absorb sunlight on one side, bifacial modules feature photovoltaic cells on both front and rear surfaces, enabling them to harvest reflected and diffuse solar radiation from the ground or surrounding surfaces. This capability enhances energy efficiency and land-use synergy in Agro-PV systems.

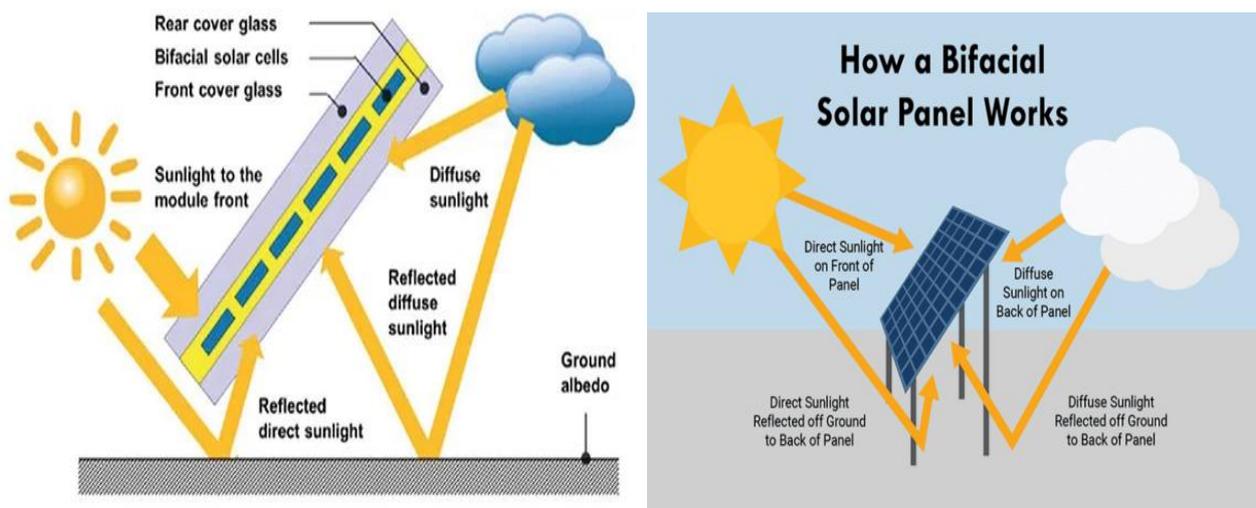


Figure 3: How a Bifacial solar panels works

Bifacial solar panels can produce 5% to 30% more energy compared to conventional panels, depending on site-specific factors such as ground reflectivity (albedo), panel elevation, orientation, and shading patterns. For example, in highly reflective environments such as light-colored soils, sand, or gravel, the rear side of bifacial panels captures substantial additional sunlight, boosting overall electricity output (Maysun Solar, 2024; NREL, 2023). Moreover, bifacial modules extend the effective power generation window by absorbing sunlight at low sun angles during morning and evening hours, contributing to a more consistent and higher daily energy yield.

In agricultural contexts, this enhanced energy production translates to greater electricity availability for farm operations, including irrigation, refrigeration, and machinery, reducing reliance on external grid power and lowering energy costs. Some farm installations have reported up to 22% increased energy output after switching to bifacial systems (Growing Solar Mist, 2025).

Bifacial modules installed in Agro-PV systems help maintain or improve crop microclimates. Their design often involves mounting panels at heights or vertical orientations that allow sufficient sunlight under the arrays for crop growth while providing beneficial partial shading that reduces heat stress and conserves soil moisture. Vertical bifacial panel arrangements, such as those pioneered by Next2Sun, allow more than 90% of the ground area to remain available for agriculture, facilitating machinery access and diversified crop production (Next2Sun, 2025; IWR Online, 2019). The shading provided under bifacial panels can reduce soil evaporation and plant transpiration, improving water-use efficiency by 15–40% in some cases. Additionally, these systems contribute to lowering the farm's carbon footprint by increasing renewable energy generation onsite, aligning with climate-resilient farming goals.

Bifacial agro-photovoltaic systems employ various configurations such as: Vertical, east-west facing bifacial panels that optimize power production in morning and evening hours while enhancing land efficiency and agricultural accessibility. Elevated horizontal or tilted bifacial arrays this balance sunlight penetration to crops beneath with maximum rear-side irradiance capture. And the optimized row spacing and ground surface treatments that enhance reflected light available to the rear panel side, improving bifacial gains.

Integration with dynamic tracking and smart control systems further boosts performance by adapting panel orientation to sunlight angles and crop requirements. Bifacial solar modules thus provide a powerful solution for maximizing energy generation and agricultural productivity on the same land footprint, enabling more sustainable, climate-smart farming practices that will likely grow in importance with advancing solar technology and digital integration.

3.3. Spectral Splitting Technology

Spectral splitting technology is a cutting-edge innovation in agro-photovoltaic (Agro-PV) systems that improves the dual use of land by selectively dividing sunlight into portions optimized for crop photosynthesis and electricity generation. This approach transcends traditional shading trade-offs by tailoring the solar spectrum to the specific needs of plants and photovoltaic (PV) cells, enhancing both crop growth and energy yield simultaneously.

Sunlight comprises a broad spectrum of wavelengths, but crops primarily use photosynthetically active radiation (PAR), mainly blue (430–470 nm) and red (640–680 nm) light for photosynthesis. Spectral splitting technology employs optical components such as dichroic mirrors, beam splitters, or specialized films to transmit these critical PAR wavelengths to crops while reflecting or directing the remaining sunlight spectrum (including green, near-infrared, and infrared wavelengths) toward PV cells for efficient electricity generation.

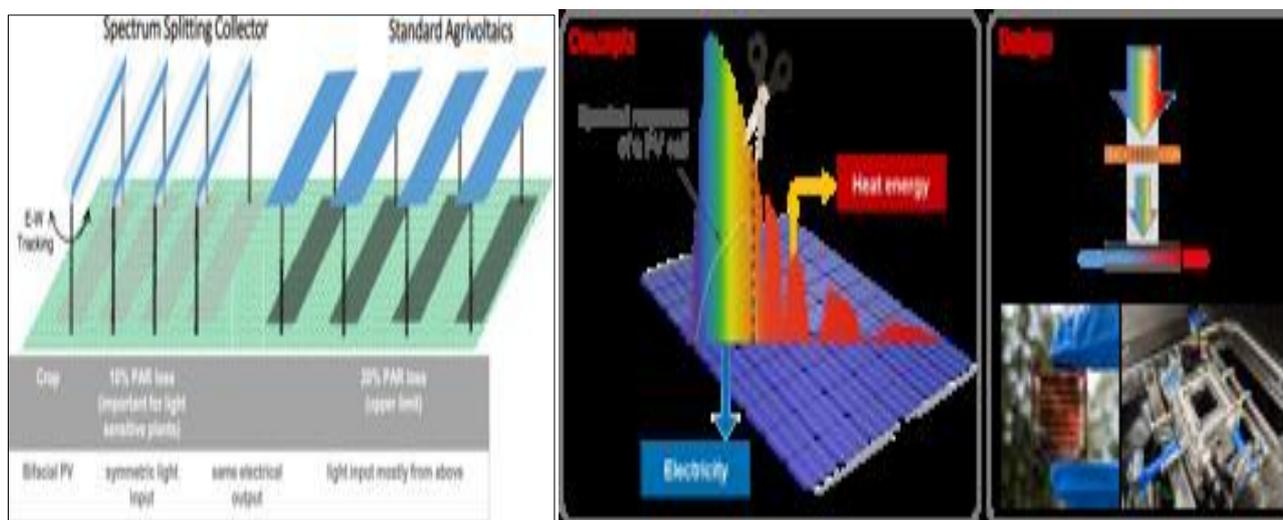


Figure 4 (a) Concept of spectral splitting PVT technology, and (b) Spectral splitting PVT design based on semi-transparent perovskite solar cells

For instance, the V-trough concentrating spectral splitting agrivoltaic system (VCSPVA) uses spectral splitting films attached to flat plates in a V-shaped trough. This system transmits red and blue light to the crops below while concentrating and redirecting other wavelengths onto solar panels. It improves solar energy use without compromising crop photosynthesis. The trough angles adjust based on the sun's elevation to maximize reflected radiation capture, thus improving overall system efficiency (Liang, X., et al., 2024). Studies show that spectral splitting agrivoltaics can increase overall solar efficiency by more than 39% compared to traditional agrivoltaic systems. For example, the VCSPVA system achieved an annual efficiency of about 17%, with power generation exceeding that of conventional PV systems by more than 45%, all while maintaining or improving crop growth (Liang, X., et al., 2024).

Field trials of spectral-splitting concentrator agrivoltaics (SCAPV) showed considerable agricultural benefits, including a 13% increase in plant biomass and nearly a 50% reduction in heat stress on plants. Crops grown under spectral splitting systems, like ginger, peanuts, sweet potatoes, bok choy, and lettuce, showed yield increases between 6.5% and almost 48%, thanks to better light quality and microclimate conditions (Zou, Z., et al., 2023; Ravishankar, H., et al., 2023).

Spectral splitting systems also provide economic value by increasing net present value and shortening payback periods due to higher energy yields and crop productivity. They also help reduce greenhouse gas emissions by increasing renewable electricity production without needing more land or negatively affecting crop output. For example, the VCSPVA setup demonstrated significant carbon emission reduction benefits along with its economic gains (Ravishankar, H., et al., 2023;

Liang, X., Hu, Y., Yao, Y., & Lv, H., 2024). By managing solar spectral components well, spectral splitting technology maximizes both crop photosynthesis and photovoltaic power generation. This innovation offers promising ways to improve land use, environmental sustainability, and economic viability in agro-photovoltaic systems, making it an important part of future food-energy solutions.

3.4. Dynamic Solar Tracking Systems

Dynamic Solar Tracking Systems enable solar panels to continuously adjust their position and tilt throughout the day, following the sun's path to maximize energy generation while considering crop light needs for proper growth. Single- or dual-axis tracking systems mechanically reposition solar panels to maintain optimal angles for sunlight. This adjustment increases total power output by up to 15% or more compared to fixed panels, ensuring efficient solar energy capture at different times and seasons (Azocleantech, 2025; PMC, 2024).

Unlike traditional tracking systems that focus only on maximizing energy, agro-PV dynamic trackers use algorithms that account for crop photosynthesis needs by adjusting shading intensity. Panels change tilt angles and height to let enough sunlight reach the crops below, preventing excessive heat or light stress while creating beneficial microclimates (PMC, 2024).



Figure 5 Dynamic Solar Tracking Systems in Agro-PV

Innovations in foldable and adjustable panel designs include foldable or height-adjustable panels that work with tracking systems. These designs offer flexibility for different crop types and seasonal changes. They allow machinery access and protect against harsh conditions like frost or hail (PMC, 2024). Advanced control algorithms analyze weather, crop, and solar data to optimize panel movements, enhancing synchronization between energy production and agricultural productivity. This approach also helps achieve steady power generation and balance demand with supply (PMC, 2024; Azocleantech, 2025).

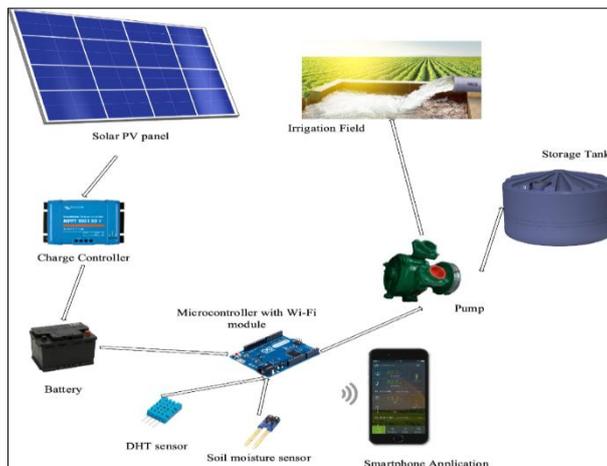
Dynamic solar tracking systems effectively address the trade-off between energy and agriculture by maximizing land efficiency, increasing renewable energy generation, and supporting stable crop growth through smart shading. Their integration is crucial for climate-smart, sustainable agro-PV developments in various environments.

3.5. Integration of IoT and Smart Sensors

Integration of IoT and Smart Sensors involves installing IoT-enabled sensor arrays across Agro-PV sites to continuously monitor key environmental factors, including soil moisture, temperature, humidity, solar irradiance, and panel performance. These sensors provide detailed, real-time data that is essential for optimizing crop microclimates and energy outputs. The collected sensor data gets transmitted wirelessly to cloud platforms where AI and machine learning algorithms analyze it to optimize irrigation schedules based on exact soil moisture and weather conditions, adjust fertilization to meet crop needs, manage crop growth phases, and anticipate stress. They also

dynamically control solar panel tilt and shading to balance energy generation with crop sunlight requirements.

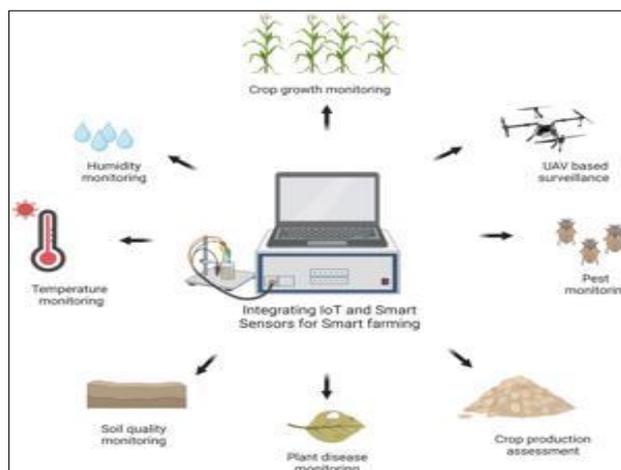
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Figure 6 A solar-powered, internet of things (IoT)-controlled water irrigation system

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Figure 7 Applications of integrated IoT and smart sensors for precision farming.

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Farmers and system operators can access real-time environmental and system performance data via user-friendly dashboards on mobile or desktop devices. This setup allows for quick detection of problems in crops or panels, remote adjustments for irrigation, shading, and panel orientation, and efficient energy use aligned with production levels. This remote monitoring reduces manual labor, ensures precise resource use, and boosts system reliability. This IoT-smart sensor integration enables data-driven, adaptive farm management that improves water and energy efficiency, strengthens crop resilience, and maximizes dual land use, which is essential for sustainability in various agro-climatic zones. These innovations together make agro-photovoltaic systems intelligent, adaptive, and sustainable smart farms capable of meeting food and clean energy needs efficiently.

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3.6. Concentrating Photovoltaic (CPV) Systems

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These Concentrating Photovoltaic (CPV) Systems use optical elements like lenses or mirrors to focus sunlight onto high-efficiency solar cells. This concentration greatly increases power output per unit of land area. It is especially suitable for regions with high solar irradiance. CPV Systems

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in Agro-PV harness lenses or curved mirrors to concentrate sunlight onto a small, highly efficient photovoltaic cell. By focusing more sunlight on a smaller cell area, CPVs achieve higher electrical conversion efficiency compared to traditional flat panels. It incorporates spectral splitting technologies that separate sunlight into bands: wavelengths beneficial for photosynthesis (mainly blue and red light) are transmitted to crops beneath, while other wavelengths are directed towards concentrated PV cells for electricity generation.

Table 1. Large-scale APV development in various parts globally. (Aritra Ghosh, 2023)

Location	System Details (capacity; Location; Crop type)
Bangladesh	3.77 MW, Soudia Agro Solar PV Power Plant 12.5 acres of land in the Pabna
China	1GW near Yellow River in the Ningxia Crop: goji berries Panels are installed 2.5 m above the land. To date, this is the largest APV system globally.
France	111 kW, TotalEnergiers and InVivo
Italy	Research Project, Overall capacity is not available
Germany	2 MW German EPC contractor Goldbeck Solar Arc-shaped PV having 2.5–3 m height
Netherlands	2.7 MW PV plant near Arnhem Corps: blueberries, red currants, raspberries, strawberries, and blackberries
Saudi Arabia	Miral solar spin-off of KAUST developed foldable solar PV for APV application
South Korea	100 KW, Three villages Guryang-ri, Duseo-myeon, and Ulju-gun Rice Modules are having 4 m height

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Fig. 8 APV application in different countries(Aritra Ghosh, 2023)

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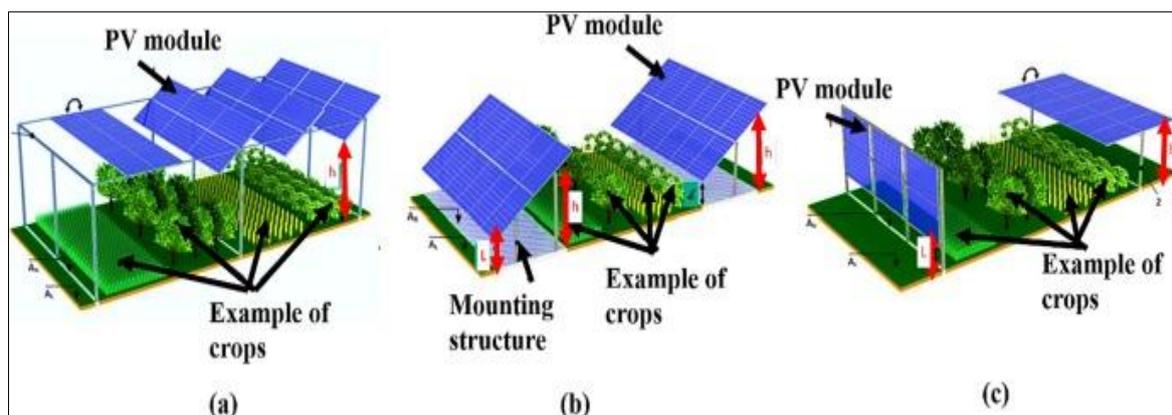


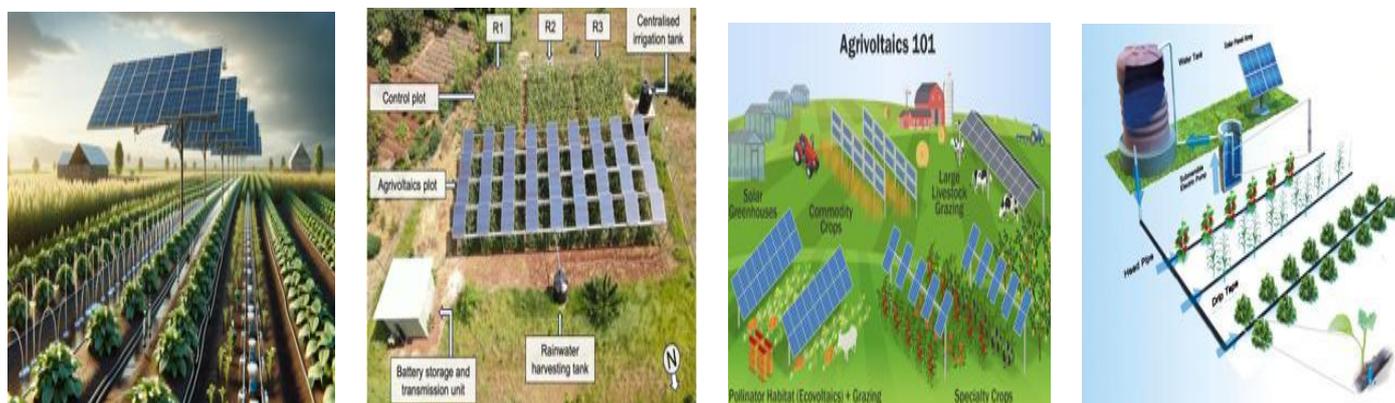
Fig. 9 Schematic illustration of APV systems design developed by DIN SPEC 91434. (a) Overhead PV with vertical clearance > 2.1 m, (b), & (c) Interspace PV with vertical clearance < 2.1 m. (Aritra Ghosh, 2023)

This design maximizes both crop growth and power output simultaneously. Typically require accurate solar tracking to maintain concentrated light on small PV cells throughout the day. Innovative designs implement dual-axis tracking to optimize incident sunlight capture, balancing energy generation with minimal shading for underlying crops. Some of its advantages are: High power density increases energy yield per land area, Enhanced synergy between farming and energy production allows efficient land use, Reduced carbon footprint thanks to cleaner energy and preserved agricultural productivity, and Economic benefits evidenced by competitive net present values and fast payback periods in pilot systems (Liang, X., Hu, Y., Yao, Y., & Lv, H. 2024; EcoGreenEnergy. 2025; Liu, et al., 2025)

The challenge with CPV is that it requires sophisticated optical components, precise alignment, and maintenance of tracking systems. Initial costs are higher but balanced by improved energy efficiency and land productivity. These CPV innovations reveal how concentrating optics and spectral management combined with precision tracking enhance the productivity and sustainability of agrophotovoltaic systems in high-irradiance regions, supporting efficient dual use of land for crops and energy.

3.7. Water Management Innovations

Key technological innovations in agro-photovoltaic (Agro-PV) system design related to Water Management Innovations play a pivotal role in enhancing water-use efficiency, conserving soil moisture, and supporting sustainable irrigation practices, critical factors especially in water-scarce or humid tropical regions.



Figures 10 Key Innovations in Water Management

- **Rainwater Harvesting from Solar Panels:** Agrivoltaic systems are increasingly designed to collect rainwater runoff from solar panel surfaces. Panels are strategically angled to channel and funnel this water into storage tanks or directly into irrigation systems, providing a supplementary water source for crops and reducing dependence on external water supplies. This water harvesting method is particularly valuable in arid zones where water scarcity limits agricultural productivity (Farmonaut, 2025).
- **Shading-Induced Water Conservation:** The partial shading of crops by solar panels reduces direct sunlight exposure on soil and plants, which lowers soil evaporation rates and plant transpiration. This microclimate modification helps conserve soil moisture, thereby decreasing irrigation demands and mitigating heat stress on crops. Studies show agrivoltaics can improve water use efficiency by 20–47% and lower soil and air temperatures by 1–4 °C (NREL, 2025; ScienceDirect, 2025).
- **Solar-Powered Smart Irrigation:** Integration of IoT-enabled sensors with agrivoltaics enables real-time monitoring of soil moisture, humidity, and temperature. AI-driven analytics then optimize irrigation scheduling and amounts, delivering precise water volumes only when and where needed. This not only reduces water waste but also lowers energy consumption for water pumping by using PV-generated electricity for irrigation infrastructure (ICARDA, 2025; Michigan Solar Partners, 2025).
- **Covering Irrigation Canals with Solar Panels:** Innovative designs include installing solar panels over irrigation canals to reduce evaporation losses and inhibit aquatic weed growth. This method conserves water in canal systems while generating electricity, creating a synergistic effect on water resource management and energy production.
- **Water Harvesting via Panel Surface Condensation:** Emerging “smart water harvesting panels” incorporate hydrophilic coatings and microstructured surfaces to capture atmospheric moisture through dew condensation, supplementing irrigation water supplies in dry environments (Al-Masalha et al., 2024).
- These water management innovations integrated into agro-photovoltaic systems enhance water-use efficiency, reduce irrigation demands, and improve crop resilience, making agrivoltaics a sustainable solution to the intertwined challenges of water scarcity, food security, and renewable energy production.

3.8. Smart Water-Harvesting Panels

Smart water-harvesting panels represent a key technological innovation in agro-photovoltaic (Agro-PV) systems that integrates efficient rainwater capture with solar energy generation, addressing critical challenges of water scarcity in agriculture while sustaining energy production. By designing photovoltaic (PV) modules to collect and channel rainwater runoff, these panels enable systems to capture water for irrigation and panel cleaning, enhancing overall system sustainability and crop productivity.

In typical Agro-PV setups, solar panels are elevated and inclined to optimize sunlight exposure. This inclination also allows rainwater to run off smoothly. Smart water-harvesting panels are designed with integrated gutters or channels fixed at the panel edges to collect the rainwater runoff efficiently. The harvested water is then directed to storage tanks, which can later supply irrigation or cleaning water. This system leverages existing infrastructure without additional land use, creating a dual water-energy harvesting approach.



Fig. 11 APV application in different countries

Advanced designs use sensors and IoT integration to monitor rainfall, water levels, and soil moisture in real time, enabling adaptive irrigation scheduling that conserves water while maximizing crop growth. The water collected can also be used for panel cleaning to remove dust and dirt, which otherwise reduces solar panel efficiency by up to 35%, particularly in arid or dusty environments. The benefits and impacts of the Smart Water-Harvesting Panels are:

- **Water Conservation:** Shading from PV panels reduces soil evaporation and plant transpiration. The extra rainwater harvesting lessens the need for irrigation during dry periods, which is especially important in arid or semi-arid regions.
- **Energy Efficiency:** Using harvested rainwater to clean the panels helps maintain their performance. This ensures consistent electricity generation.
- **Enhanced Crop Yields:** A reliable water supply supports stable crop growth under the panels, which might struggle with limited water.
- **Cost Savings & Sustainability:** Integrating water systems lowers dependence on outside irrigation water. This reduces farm operation costs and environmental impact.

Studies report rainwater harvesting efficiencies of **70-80%** depending on system design, panel area, and local rainfall. One agro-voltaic system developed with metal sheet water channels, underground conveyance pipes, and large-capacity storage tanks can provide irrigation water covering up to 1 acre, sufficient to support crop irrigation and panel cleaning needs (International Journal of Innovations in Engineering and Science, 2022; Ogundele, O., et al. 2024). IoT-enabled management further enhances precision irrigation, optimizing water use by tailoring supply to crop demand, monitored environmental parameters, and weather forecasts.

3.9. Vertical and Interspace Panel Arrangements

Key technological innovations in agro-photovoltaic (Agro-PV) system design related to Vertical and Interspace Panel Arrangements focus on optimizing land use efficiency by innovatively positioning solar panels to maximize simultaneous agricultural production and solar energy generation.



Fig. 12 Vertical and Interspace Panel Arrangements

a) Vertical panels are installed upright, often in rows aligned east-west, allowing solar panels to be bifacial and capture sunlight on both sides. This configuration offers several advantages such as, occupying minimal ground space linearly, leaving over 90% of the area available for crop cultivation compared to over 70% area coverage by traditional south-facing fixed tilt panels (Next2Sun, 2025). Capturing diffused and reflected light and reduce midday shading, thus providing more evenly weighted light on crops throughout the day. The vertical setup allows sunlight penetration in the early morning and late afternoon, benefiting plant photosynthesis cycles. Lastly, since panels are narrow and upright with adequate spacing (e.g., 8 meters or more apart), farm machinery can pass between rows, minimizing disruption to farming practices.

Vertical panels tend to have lower energy capture efficiency during midday when sun angles are high due to less optimal incidence angles. Also, vertical structures may require careful design to avoid crop shading and interference. They typically don't provide crop weather protection like elevated canopies or greenhouse roofs. And, they are particularly suitable for crops tolerant to partial shading and in regions where maximizing available land for cultivation is critical.

b) The Interspace arrangements involve strategic spacing between solar panel rows to optimize crop light exposure and farming operations. Rows of panels are spaced sufficiently apart (e.g., several meters) to allow adequate sunlight between panels and permit machinery passage. Spacing can be optimized based on crop type, panel height, and tilt angles. And some designs use staggered or alternating panel placement to increase light diffusion, reduce excessive shading, and improve microclimate conditions beneficial for crops. Interspace complements adjustable-height and tilt-able panels to fine-tune light and shading patterns dynamically, enhancing both energy yield and crop growth.

3.10. Modular and Lightweight Structures

Modular and lightweight structures are crucial technological innovations advancing the feasibility, scalability, and adaptability of agro-photovoltaic (Agro-PV) systems. Modular design divides large PV arrays into smaller, standard units that can be easily put together, replaced, and scaled to meet specific farm needs. This modular approach allows for flexible installation on uneven ground or unusual crop layouts. It also supports retrofitting agrivoltaic systems onto existing agricultural structures without needing extensive changes to the site. Lightweight, modular designs in agriculture offer several benefits: Elevated, lightweight structures maintain enough height for machinery, workers, and natural crop growth. For instance, lightweight modules attached to protective net frameworks let traditional orchard practices continue without interruption. Additionally, they reduce the need for heavy custom substructures. Simplifying installation lowers initial costs and labor expenses, speeding up project timelines (Basler, Fraunhofer ISE project lead).

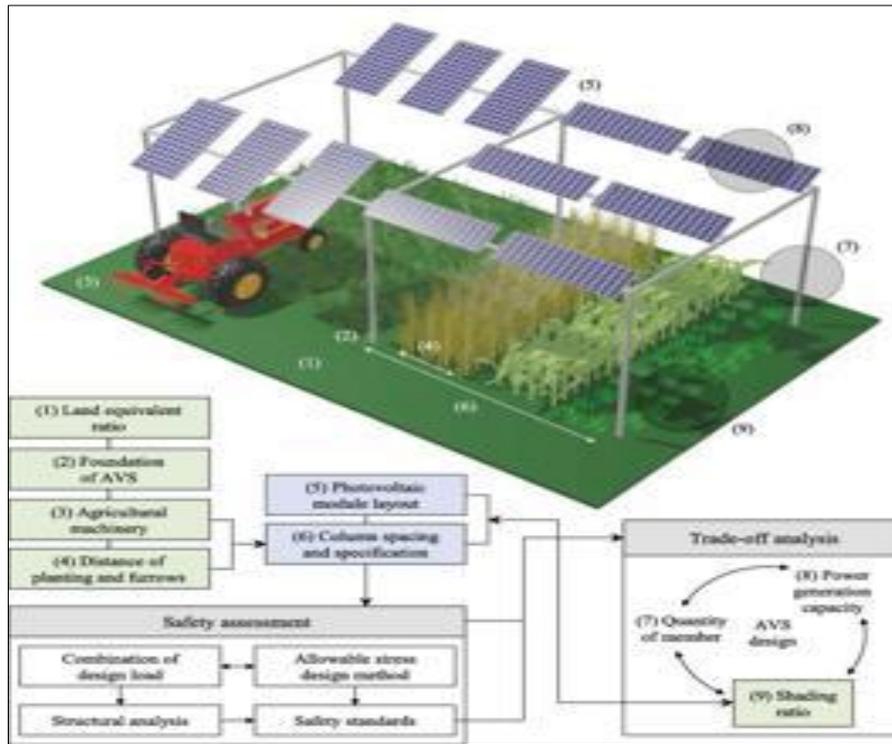


Fig. 13 Conceptual design of an agrivoltaic system (AVS)

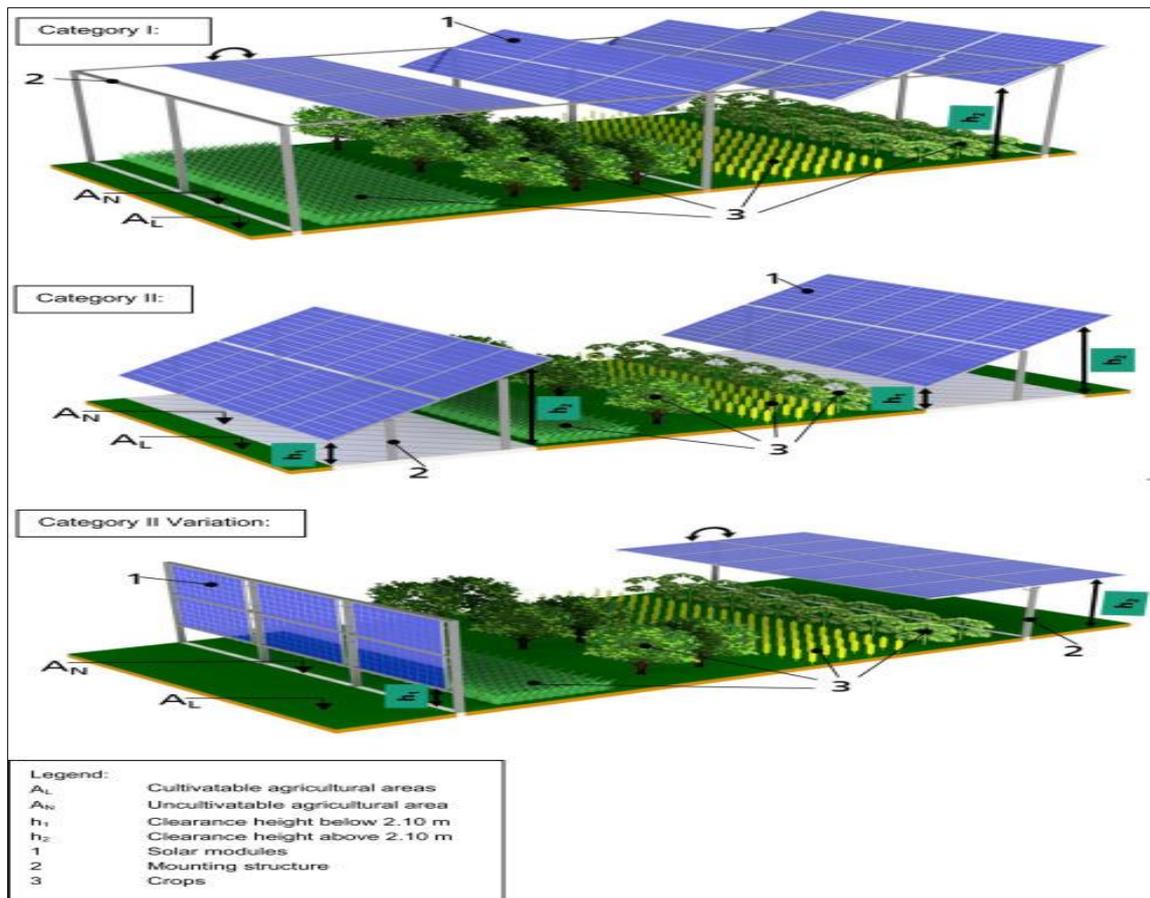


Figure 14. Main agrivoltaic systems

Finally, lightweight shading structures provide partial solar protection, which helps lower heat stress and conserve soil moisture. This can improve crop yield in changing climates. These structures can also be stored or adjusted seasonally to enhance airflow and light availability. A demonstration in a cherry orchard in southern Germany showed positive results. Lightweight modules were mounted directly on existing weather protection steel frames without affecting electricity output or the quality of the fruit harvest. Lightweight, modular designs enable: - Scalable energy capacity: For example, these structures have shown installation densities of about 420 kW per hectare, providing significant renewable energy while preserving agricultural land use. - Customizable layouts: Modules can be set up in rows or grids that follow the crop rows, ensuring optimal sunlight distribution and shading tailored to the needs of different crop species. - Integration with smart management: With sensor networks and IoT devices, these structures help with dynamic panel positioning, cleaning, and irrigation control through lightweight actuators, promoting more precise farming. Modular and lightweight structures mark an important change in Agro-PV system design, tackling structural and economic challenges while maintaining agricultural integrity. Their capacity to retrofit existing infrastructure, simplify installation, and allow for flexible scaling makes them key innovations for sustainable, climate-resilient agrivoltaic deployment worldwide.

7. Comparative Analysis

The comparative analysis of agro-photovoltaic (Agro-PV) system technologies focuses on evaluating their energy yield, crop yield, land use efficiency, alongside a cost-benefit analysis, applicability across different climates and crop types, and the advantages and limitations of each innovation.

7.1. Energy Yield

Bifacial solar panels significantly enhance energy output by capturing sunlight from both front and rear sides, increasing electricity generation by 15-30% compared to traditional monofacial panels (Farmonaut, 2025). Spectral splitting technology offers a dual benefit by transmitting photosynthetically active radiation (PAR) for crop growth while converting other wavelengths into electricity, achieving overall system efficiencies close to 17%, up to 39% higher than conventional agrivoltaic systems (Liang et al., 2024). Dynamic solar tracking systems improve daily energy yields by 10-20% by following the sun's path and adjusting panel tilt (Azocleantech, 2025). Concentrating photovoltaic (CPV) systems excel in high irradiance regions by focusing sunlight to boost power density, although their efficiency depends heavily on precise tracking and climatic conditions (Liang et al., 2024).

7.2. Crop Yield and Land Use Efficiency

Systems with adjustable-height and tiltable panels enable dynamic light management, reducing shading stress and improving microclimates; studies report crop yield improvements of 5-15% due to better light distribution and moisture conservation (Santra et al., 2025). Vertical and inter-space panel arrangements optimize land availability by occupying less ground space and allowing more sunlight penetration, supporting high-density farming with minimal shading impact (Next2Sun, 2025). Crop yields vary by species but commonly show resilience or enhancement under these configurations. While IoT-enabled precision irrigation integrated with solar arrays contributes to water-use efficiency gains of 20-40%, indirectly supporting crop productivity in water-limited environments (Sheikh Mansoor et al., 2025).

7.3. Cost-Benefit Analysis

Bifacial panels incur higher initial costs but achieve faster returns due to increased energy yield and extended lifespans (Maysun Solar, 2024). Spectral splitting and CPV systems, while technologically advanced, often involve greater upfront investment in specialized components and tracking mechanisms, limiting adoption primarily to high irradiance and high-value cropping areas (Liang et al., 2024). Dynamic trackers increase complexity and maintenance costs but can boost

overall system profitability by maximizing energy output and crop production synergy (Azoclean-tech, 2025). Modular, lightweight structures and IoT integrations tend to reduce operational expenses by streamlining installation and enabling predictive maintenance, though initial setup may require sophisticated infrastructure (PMC, 2024; Sheikh Mansoor et al., 2025).

7.4. Applicability across different climates and crop types

Agro-photovoltaic (Agro-PV) system technologies finds applicability in Various Climates and Crops, such as in Tropical and arid regions benefit greatly from CPV and water-harvesting panels that enhance energy yield and provide supplemental irrigation (Al-Masalha et al., 2024). Temperate zones with variable sunlight see optimal performance from tilttable and tracking systems that adjust panel orientation seasonally (Green Dealflow, 2024). Vertical panel designs are suited for areas with limited land availability and certain partial shade-tolerant crops (Next2Sun, 2025). And finally, in diverse crops such as leafy greens, berries, and grapes have shown compatibility with agro-PV systems, whereas light-demanding crops may require spectral splitting or adjustable shading for optimal growth (Farmonaut, 2025).

Table 2: Advantages and limitations of each innovation

Technology	Advantages	Limitations
Bifacial Solar Panels	Increased energy yield; uniform shading; improved microclimate	Higher cost; ground reflectivity affects rear-side gain
Spectral Splitting Tech	Maximizes energy and crop growth; supports PAR optimization	Complex optics; higher cost; limited commercial maturity
Dynamic Solar Trackers	Maximizes incident sunlight; adaptive shading for crops	Maintenance intensive; increased mechanical complexity
Concentrating PV Systems	Very high power density; efficient for high irradiance regions	Expensive optics; tracking required; sensitive to diffuse light
Adjustable-Height/Tilttable Panels	Flexible light and shading control; supports diverse crops	Structural complexity; higher initial cost
Vertical/Interspace Panels	Maximizes arable land; easy machinery access; partial crop shading	Lower energy capture at high sun angles; suitability varies by crop
IoT & Smart Sensors	Real-time monitoring; precision agriculture; operational efficiency	Requires connectivity; initial investment in technology

8. Challenges and Research Gaps

Agro-photovoltaic (Agro-PV) systems are an innovative technology that couples solar energy production with agriculture on the same land. While promising significant benefits in sustainable food and energy production, Agro-PV implementation faces several technical challenges, economic and policy obstacles, environmental and social considerations, and areas requiring further research for wide adoption and optimization.

8.1. Technical Challenges

Balancing the solar energy captured by photovoltaic panels with sufficient sunlight transmission for crop photosynthesis is a core challenge. Poorly designed panel placements can result in excessive shading, limiting photosynthetically active radiation (PAR) and reducing crop yields (Azocleantech, 2025). The spatial heterogeneity of shading under PV panels means crops experience dynamic light conditions that differ from natural shade, affecting growth and microclimate unpredictably. Controlling shading patterns dynamically or through technologies like spectral splitting is complex but necessary for optimal dual use (NREL, 2023).

Designing robust yet adaptable mounting structures that accommodate adjustable heights, tilts, and tracking mechanisms poses engineering challenges. Agro-PV structures must withstand

environmental stressors (wind, rain, hail) without damaging crops or panels (Azocleantech, 2025). Additionally, agricultural activities such as machinery passage and fieldwork can cause mechanical wear on panels, increasing maintenance needs and costs. Regular cleaning to avoid dust accumulation is critical as dirt can reduce panel efficiency by up to 35% annually (NREL, 2023; UTRGV, 2024). Maintenance complexity increases when integrating IoT, dynamic tracking, or water harvesting systems.

8.2. Economic and Policy Barriers

High initial capital costs for Agro-PV systems reported to be 5-40% higher than conventional PV installations limit adoption, especially by smallholder farmers with limited financial resources (Azocleantech, 2025). Specialized structures, dual-use site planning, and integration of tracking or sensor networks add to expenses. Furthermore, unclear or inconsistent land-use policies, zoning regulations, and subsidy frameworks complicate project development and financing, especially where agrivoltaics overlap with agricultural land classifications or conservation areas. Farmer acceptance is impacted by financial uncertainty and unfamiliarity with technical operations (Azocleantech, 2025).

8.3. Environmental and Social Considerations

While Agro-PV can improve water-use efficiency by reducing evapotranspiration via shading, it may also alter soil moisture dynamics and microclimate in ways not yet fully understood or predictable across different crops and environments (NREL, 2023). The choice of compatible crops is critical; some light-demanding plants perform poorly under panels, restricting crop diversity and potentially impacting local food systems. Social acceptance depends on trust, education, and ensuring equitable participation in benefits. Concerns about land tenure, changes in agricultural labor practices, and landscape aesthetics pose social challenges requiring stakeholder engagement and policy support.

8.4. Areas Lacking Sufficient Research

There is limited knowledge about the physiological responses of many crops, especially under dynamic shading and spectral modification conditions. Research is needed on a wider variety of crops beyond common test species (NREL, 2023). Studies on long-term impacts of agrivoltaic systems on soil health, crop yields, and energy economics are scarce, limiting modeling of sustainability and scalability (Azocleantech, 2025). More work is needed on optimal combinations of structural design, tracking, IoT sensor management, and water harvesting technologies to develop site-specific, cost-effective solutions. Research on regulatory approaches and incentive models that encourage adoption while ensuring environmental and social benefits is required.

9. Future Trends and Research Opportunities

Agro-photovoltaic (Agro-PV) systems are rapidly evolving, driven by emerging technologies, global sustainability goals, and the urgent need for climate-resilient agricultural practices. The future of Agro-PV

holds promising avenues that integrate artificial intelligence, robotics, precision farming, and innovative system designs to enhance energy and crop productivity sustainably. This section explores these future trends and research opportunities focusing on technological integration, climate resiliency, and scalability.

The integration of AI, robotics, and precision agriculture technologies is poised to revolutionize agrophotovoltaics by enabling intelligent, adaptive system management. AI-driven algorithms can optimize solar panel positioning dynamically based on real-time solar irradiance, weather patterns, and crop light requirements, maximizing both energy yield and photosynthetic efficiency (Farnonaut, 2025). Advanced robotics could automate panel cleaning, maintenance, and monitoring tasks, reducing labor costs and enhancing operational efficiency.

Precision farming tools, such as IoT-enabled soil moisture sensors, microclimate monitors, and drone based crop health imaging, are being integrated with Agro-PV systems to tailor irrigation, fertilization, and shading on a site-specific basis (Sheikh Mansoor et al., 2025). This convergence enables data-driven decision-making that optimizes resource use, reduces waste, and boosts crop resilience, supporting sustainable intensification of food and energy production on limited land. Agro-PV systems contribute significantly to climate-resilient agriculture by providing protective shading that mitigates heat stress and reduces evapotranspiration, thus conserving soil moisture in increasingly arid and heat-prone regions (Azocleantech, 2025). The PV arrays act as physical barriers against extreme weather events, such as hailstorms and heavy rainfall, protecting sensitive crops. Furthermore, by generating renewable energy onsite, Agro-PV systems enable decarbonization of farm operations, supporting climate mitigation goals. Combined with adaptive AI controls, these systems can dynamically adjust shading and irrigation schedules to buffer crops against climatic variability. This resilience not only sustains yields under challenging conditions but also enhances water-use efficiency by 15-40% (Farmonaut, 2025). Market projections estimate that the agrivoltaics market will grow significantly, driven by technological advances and increasing policy support. The global agrivoltaics market is expected to reach multi-billion-dollar valuation by 2030, with compound annual growth rates exceeding 11% (GlobeNewswire, 2025). Scalability hinges on modular, lightweight, and adaptable structural designs that accommodate diverse crops and farming systems while enabling widespread adoption. Research opportunities exist in developing cost-effective, standardized installation kits and improving interoperability between solar technologies and agricultural machinery. Additionally, integrating renewable energy storage and smart grid interfaces will support farmers' energy autonomy and grid stability. Sustainability also requires advances in materials science (e.g., durable, transparent PV modules), water-harvesting panels, and hybrid systems combining agronomy with energy production to enhance ecosystem services. The adoption of policy frameworks and incentive programs tailored to agro-PV deployment in diverse agroclimatic zones will further facilitate long-term scalable growth (NREL, 2023).

10. Conclusion

This survey has highlighted the rapid advancements in agro-photovoltaic (Agro-PV) system design, emphasizing key technological innovations such as adjustable-height and tiltable solar panels, bifacial and spectral splitting technologies, dynamic solar tracking, and the integration of IoT-enabled smart sensors. These innovations collectively enhance the dual land-use efficiency by optimizing energy output and crop productivity while promoting water conservation and microclimate regulation. The comparative analysis reveals that tailored solutions combining several of these technologies yield the best balance between renewable energy generation and sustainable agriculture, adaptable across diverse climatic zones and crop requirements. From a research perspective, the findings underscore the need for more crop-specific studies, long-term performance assessments, and system integration optimization to address unresolved challenges in light management, structural durability, and cost reduction. Industry players are encouraged to focus on scalable, modular designs with embedded smart technologies that lower operational complexity and cost. Policymakers should develop supportive frameworks that clarify land-use regulations, incentivize agro-PV adoption, and promote interdisciplinary collaboration to accelerate deployment while safeguarding environmental and social interests. By bridging innovative engineering with agricultural sustainability and climate resilience, agro-photovoltaics represent a promising pathway toward integrated food and energy security in the face of increasing global challenges.

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