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Agrivoltaics: A promising farming system for the western arid regions of India

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'Agrivoltaics' integrates agriculture with solar energy production, addressing critical challenges like water scarcity, land-use conflicts, and climatic extremes in arid regions. This system enhances land-use efficiency, mitigates microclimatic stress, and provides dual income through crops and renewable energy. Its relevance lies in fostering sustainable agriculture, energy security, and economic resilience for resource-constrained farmers. Aligning with global sustainability goals, offers a transformative solution to balance food production and energy needs while promoting environmental conservation and rural development.

Keywords: Agrivoltaics, Arid regions, Land-use efficiency, Renewable energy, Sustainable agriculture

THE arid regions of western India, particularly western Rajasthan, face significant challenges in sustainable agriculture due to extreme heat, limited rainfall, and poor soil fertility. Farmers in these areas often struggle with erratic crop yields, relying heavily on scarce water resources and traditional farming methods. In this context, 'agrivoltaics' is a system that integrates agriculture with solar energy production and has emerged as a promising solution. By enabling the simultaneous use of land for both crop cultivation and solar power generation, 'agrivoltaics' offers a dual approach to enhance farmer livelihoods and promote sustainable development.

'Agrivoltaics' involves installing solar panels on agricultural land, allowing the concurrent production of food and renewable energy. This dual land-use strategy is particularly relevant in arid regions like western Rajasthan, where natural resources such as water and arable land are limited. The region experiences annual rainfall of less than 250 mm, with over 60% of the land classified as arid or semi-arid. These harsh climatic conditions lead to frequent crop failures and economic hardships for farmers. Integrating solar panels with agriculture can create microclimates that reduce soil evaporation, provide avenues for rain water harvesting and improve water-use efficiency, thereby enhancing agricultural productivity. Additionally, the renewable energy generated provides farmers with an extra income source, contributing to economic resilience.

Thus, 'agrivoltaics' presents a viable strategy to address the entangled challenges of agricultural productivity and profitability in arid regions. By optimizing land use for both crop cultivation and solar power generation, this approach supports sustainable

Ground mounted Agrivoltaic system at ICAR-CAZRI, Jodhpur development and improves the livelihoods of farmers in these resource constrained areas.

Concept of 'agrivoltaics'

'Agrivoltaics' is an innovative land-use strategy that allows the simultaneous harvesting of solar electricity and cultivation of crops, effectively addressing land-use conflicts and promoting sustainable agricultural practices. The design of agrivoltaic systems involves strategically placing photovoltaic (PV) panels at specific angles and configuration to optimize sunlight distribution between crops and PV panels. Ground-mounted structures are more feasible in arid regions due to the lower cost of panels and the frequent need for washing to remove aeolian dust deposition. To optimize efficiency, PV modules should be arranged in an East-West orientation and inclined southward at a tilt angle equal to the latitude of the location. Based on the zenith and azimuth angles observed on December 22, the recommended minimum spacing between PV arrays in western India is approximately 3 meters for single-row arrays, 6 meters for two-rows arrays, and 9 meters for three-rows arrays. Additionally, a ground clearance of around 0.5 meters is advised for optimal performance.

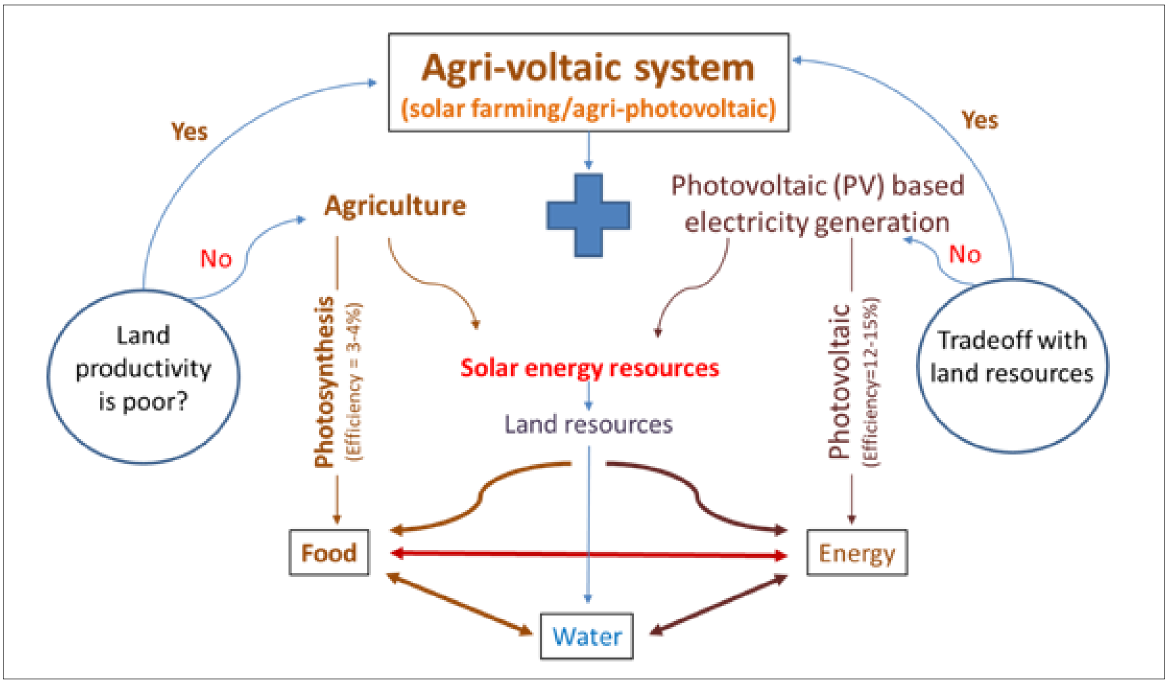
This configuration provides 25-30% below panel area and 65-70% interspace area of total net area of PV plant that can be utilized for cultivation of different crops according to shade tolerance. Additionally, the panels provide shade, which can protect crops from extreme weather conditions such as high winds and intense heat, thereby creating a more favorable microclimate. This shading effect also helps in reducing soil temperature and minimizing water evaporation, conserving essential moisture for crops.

The dual benefits of 'agrivoltaics' make it an attractive option for both farmers and policymakers. On-site renewable energy generation can power agricultural operations like irrigation systems and processing units, reducing reliance on non-renewable energy sources and lowering operational costs. Moreover, the moderate microclimate under the panels enhances crop resilience against climatic extremes, potentially leading to improved yields and reduced risk of crop failure.

In regions facing resource constraints, agrivoltaics offers a sustainable solution by optimizing land use and providing a pathway towards climate-resilient agriculture and renewable energy generation. Its adaptability to various crops and climatic conditions enhances its potential as a key component in sustainable development strategies worldwide.

Significance of 'agrivoltaics' in arid regions

Climatic challenges: Arid western regions, one of the driest regions in India, faces severe climatic challenges that directly impact its agricultural productivity. Rainfall in this region averages less than 250 mm annually and is typically concentrated in short, intense spells. These erratic rainfall patterns, combined with prolonged dry periods, result in frequent crop failures. High temperatures, often exceeding 45°C during summer, exacerbate the stress on crops. The intense heat accelerates evaporation rates, drying up limited water reserves, thereby further reducing soil moisture essential for plant growth. Water scarcity is another critical challenge. The fresh groundwater resources are deep and meagre, while surface water resources remain insufficient to meet the demands of agriculture. Such extreme conditions highlight the pressing need for interventions that can explore available natural resources optimally to ensure agricultural sustainability in the regions. 'Agrivoltaic' systems offer a promising solution by reducing soil evaporation through shading



Conceptual framework of agri-voltaic systems: Integration of solar energy for simultaneous food and energy production while optimizing land and water resources and conserving water resources. Additionally, solar energy generated by these systems can power efficient irrigation methods, such as drip irrigation, further optimizing water use.

Energy need and generation potential: In arid regions like western Rajasthan, access to reliable and affordable energy is vital for sustaining agriculture. Electricity is a major input cost, particularly for irrigation, and other mechanized farm operations. The rising costs of conventional electricity and the environmental impact of fossil fuels make renewable energy an attractive alternative. Besides, in the western arid regions of the country, where solar irradiance ranges from approximately 5.5 to 6.2 kWh m^{-2} day^{-1}, with almost 300 days a year being cloud-free sunny days, the average PV generation is around 4 to 5 kWh kWp^{-1} day^{-1}. This highlights the significant PV-based electricity generation potential of the region. In this scenario, 'agrivoltaics' enables farmers to generate their own electricity on-site to operate irrigation pumps, reducing energy costs significantly and creating an additional revenue stream for them through sale of surplus energy produced to grids. This dual benefit of cost reduction and income generation underscores the economic viability of 'agrivoltaics' in these resource-constrained regions.

Addressing land-use conflicts: High solar insolation in arid regions makes them ideal for PV energy generation. As ground mounted PV have become the cheapest source of power generation worldwide, solar PV generation becomes a land-intensive venture. The land required for generation of 1MW Solar energy is around 2 ha. Hence, such large tracts of land required for solar PV often compete with agricultural land, leading to land-use conflicts. This is particularly problematic in arid regions, where fertile land is already scarce. 'Agrivoltaics' offers a solution by combining solar energy generation with agricultural production on the same plot of land. By integrating these two functions, agrivoltaics not only resolves land-use conflicts but also enhances the productivity of limited resources.

Advantages of 'agrivoltaics'

***Enhanced land-use efficiency*:** Agrivoltaics enhances the productivity of land resources by up to 60% compared to standalone farming or solar installations. The Land Equivalent Ratio of agrivolatics is estimated to be 1.42 and 1.62 with only interspace area and for both interspace and below panel area, respectively.

***Mitigation of microclimatic extremes*:** Solar panels reduce ground temperatures by 2-4°C, creating a favourable microclimate for crops. In regions like arid Rajasthan, this shading effect can significantly reduce heat stress, improving crop survival rates.

***Higher water-use efficiency*:** By shielding the soil from direct sunlight, solar panels reduce evaporation, conserving water and improving soil moisture retention. Research indicates that 'agrivoltaics' can save up to 20% of irrigation water. Additionally, rainwater harvested from the surface area of PV panels, with an estimated efficiency of approximately 65-70%, can be reused for washing the panels and irrigating crops.

***Diversified income sources*:** Farmers earn income from crop sales and by selling surplus electricity generated by solar panels to the grid.

***Environmental benefits*:** Agrivoltaics reduces greenhouse gas emissions by replacing fossil fuel-based energy with renewable energy. Studies indicated that 'agrivoltaics' generates 93.1% and 83.5% less CO_2 per unit of electricity generation over hard-coal and natural gas, respectively.

***Enhanced PV energy efficiency*:** Maintaining vegetation between and underneath the PV panels creates cooling effect through evapotranspiration, thus reducing surface temperatures and improving PV efficiency by 3-5% during peak summer months.

Rain-water harvesting provision on the PV panels

Crops suitable for agrivoltaic systems

Crops that are short in stature, tolerant to partial shading, have low light requirements, and exhibit resilience to heat and drought are essential for optimizing productivity in 'agrivoltaics'. Moreover, fast-growing crops with short growth cycles align well with seasonal energy production, while high-value cash crops can enhance farm profitability. Additionally, plants with high evapotranspiration rates can help cool solar panels, boosting energy efficiency and panel longevity. The suitable crops for 'agrivoltaics' are enlisted in Table 1.

Table 1. Suitable crops for 'agrivoltaics' in western Rajasthan

Production scenario	Field crops	Vegetables	Spices and medicinal crops
Rainfed	Mung bean, moth bean, cluster bean Taramira	Amaranth, snap melon	*Aloe vera*
Irrigated	Chickpea	Bottle gourd, ridge gourd, spinach, carrot, radish, onion	*Aswagandha*, cumin, *isabgol*

Challenges and limitations of agrivoltaics

- ***High initial investment costs*:** Establishing agrivoltaics systems requires substantial upfront expenses. For marginal farmers, these costs can be prohibitive without government subsidies.
- ***Technical integration challenges*:** Proper alignment

Moth bean

Isabgol

Ashwagandha

Onion

Different crops in agrivoltaics system

Bottle gourd in semi-bower system on leeward side of PV panels

and height of panels are crucial to balance sunlight distribution for crops and maximize energy generation. Inadequate planning can diminish both crop yields and PV efficiency.

- ***Aeolian dust deposition*:** In arid regions, dust accumulation on solar panels can reduce efficiency by up to 25%. Regular cleaning increases operational costs and poses challenges in water-scarce areas.
- ***Awareness and training gaps*:** Insufficient knowledge about agrivoltaics hinder its adoption and effective system maintenance.
- ***Policy and infrastructure constraints*:** Existing renewable energy policies often overlook the dual-use nature of 'agrivoltaics'. Inadequate grid connectivity and energy storage infrastructure in rural areas further impede adoption.
- ***Land-use and crop compatibility*:** Not all crops thrive under 'agrivoltaics', hence selection of shade-tolerant, high-value crops is necessary to maximize the profitability.

Policy support and future prospects

***Government schemes and incentives*:** The PM-KUSUM (*Kisan Urja Suraksha evam Utthaan Mahabhiyan*) scheme, launched in 2019, has been a key initiative in promoting renewable energy within the agricultural sector in India. Under the scheme, ground-mounted, grid-connected solar power plants with individual plant sizes ranging from 500 kW to 2 MW are being established by individuals and Farmer Producer Organizations (FPOs) in collaboration with local distribution companies (DISCOMs). The financial structure of the scheme includes a 60% subsidy from the government, 30% through bank loans, and a 10% contribution by the plant owner. To further incentivize participation, the Ministry of New and Renewable Energy (MNRE) provides a Procurement-Based Incentive (PBI) of ₹0.40 per kWh or ₹6.60 lakh per MW annually for the first five years to DISCOMs for purchasing power from farmers or developers. Expanding the scope of such initiatives to encompass agrivoltaic projects could significantly enhance adoption, especially among small and marginal farmers.

Public-private partnerships: Partnerships between government agencies, private companies, and research institutions can play a pivotal role in scaling agrivoltaic systems. Private sector involvement can drive down costs through economies of scale, while research institutions can develop region-specific solutions.

Research and innovation: Continuous research and innovation are essential for advanced solar panel designs, such as semi-transparent or tiltable panels, can improve light distribution and efficiency. Similarly, research should also focus on designing dust-resistant solar panels, to overcome challenges like aeolian dust deposition in arid zones.

Alignment of agrivoltaics with the principles of IFS

'Agrivoltaics' exemplifies the essence of IFS by harmonizing agriculture and solar energy to enhance sustainability, economic viability, and environmental resilience. It offers a futuristic model for resource-constrained areas, aligning with national and global priorities for sustainable development (Table 2).

Table 2. Alignment of 'agrivoltaics' with the principles of IFS

Principle of IFS	How Agrivoltaics Aligns
Integration of enterprises	Combines crop production and solar energy, optimizing resources and diversifying outputs.
Resource use efficiency	Enhances land use efficiency, conserves water, and supports farm energy needs with solar power.
Sustainability and risk diversification	Moderates microclimatic extremes and provides dual income streams to reduce farm risks.
Compatibility with other farming systems	Supports intercropping, and livestock grazing under solar panels.
Multi-output system	Produces food, fodder, renewable energy, and ecosystem services like nutrient mineralization and reduce carbon emission.
Economic viability	Generates dual income from crops and electricity while reducing costs for water and inputs.
Enhancing farm resilience	Protects against climate extremes and ensures long-term sustainability with renewable energy.
Contribution to SDGs	Supports SDG 2 (Zero Hunger), SDG 7 (Clean Energy), and SDG 13 (Climate Action).

Agrivoltaics: Advancing UN sustainable development goals

'Agrivoltaics' aligns closely with several United Nations Sustainable Development Goals (UN-SDGs), advancing global efforts for sustainability (Table 3).

Table 3. Alignment of 'agrivoltaics' with UN-SDGs

UN-SDG	Alignment with 'Agrivoltaics'
SDG 1: No Poverty	Provides additional income through solar electricity and crop yields.
SDG 2: Zero Hunger	Enhances food security with optimized land use and microclimatic benefits.
SDG 7: Affordable and Clean Energy	Enables renewable energy generation, reducing fossil fuel reliance.
SDG 8: Decent Work and Economic Growth	Creates jobs in solar installation and maintenance, boosting rural economies.
SDG 9: Industry, Innovation, and Infrastructure	Promotes R&D in PV panel design, installation, PV coating and maintenance.
SDG 12: Responsible Consumption and Production	Promotes dual land use, reducing environmental impact.
SDG 13: Climate Action	Reduces carbon emissions and enhances climate resilience.
SDG 15: Life on Land	Supports sustainable land use and biodiversity conservation.
SDG 17: Partnerships for the Goals	Encourages collaboration among stakeholders for 'agrivoltaic' adoption.

SUMMARY

'Agrivoltaics' is emerging as a sustainable farming system for arid regions, particularly in western Rajasthan, addressing climatic challenges, energy needs and land use conflicts between food and energy. 'Agrivoltaics' integrates agriculture and solar power generation, optimizing land use and creating favourable microclimates that reduce soil evaporation, conserve water, and improve crop productivity. It enables farmers to generate on-site renewable energy, reducing energy costs and providing an additional income source through electricity sales. The system supports resource efficiency, enhances land use efficiency by up to 60%, and mitigates microclimatic extremes, aiding in crop resilience. However, challenges such as high initial costs, technical complexities, and dust deposition on solar panels are constraints for its adoption and efficient functioning. Benign policy support, research, and public-private partnerships are critical for scaling up adoption of 'agrivoltaics' in arid regions. 'Agrivoltaics' also aligns with principles of the Integrated Farming System (IFS) and several UN-SDGs, making it a promising farming system model for sustainable agriculture and renewable energy in resource-constrained areas.

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