Agri Articles

(e-Magazine for Agricultural Articles)

Volume: 06, Issue: 01 (JAN-FEB, 2026)

Available online at http://www.agriarticles.com

Agrivoltaic Farming: Integrating Solar Energy Production with Sustainable Agriculture

*R. Rajalakshmi, Sherly. J, V. Kanthaswamy and E. Venkadeswaran

Pandit Jawaharlal Nehru college of Agriculture and Research Institute, Karaikal, UT of Puducherry, India

Corresponding Author's email: rajilakshmiramesh2810@gmail.com

Agrivoltaic farming, also known as agrisolar or dual-use solar agriculture, is an emerging land-use strategy that integrates photovoltaic (PV) power generation with agricultural crop production on the same land unit. With increasing pressure on land resources due to population growth, climate change and expanding renewable energy infrastructure, agrivoltaic systems offer a promising solution to balance food security and clean energy goals. By elevating or strategically spacing solar panels above croplands, these systems enable simultaneous electricity generation and agricultural cultivation, while modifying microclimatic conditions such as light intensity, temperature and soil moisture. Scientific studies indicate that agrivoltaics can improve land-use efficiency, enhance crop resilience to heat and water stress and reduce evapotranspiration losses. The suitability of agrivoltaic systems varies with crop type, panel configuration, climatic region and management practices. This article provides a comprehensive scientific overview of agrivoltaic farming, including its principles, system designs, crop responses, environmental benefits, economic implications and challenges. The role of agrivoltaics in climate-smart agriculture and sustainable rural development is critically discussed, highlighting its potential as a transformative approach for future farming systems.

Keywords - Agrivoltaics; Dual land use; Solar photovoltaic systems; Climate-smart agriculture; Sustainable farming; Renewable energy integration

Introduction

The global demand for both food and energy are increasing rapidly due to population growth, urbanization and industrial development. Agriculture currently occupies nearly 40 per cent of the world's land surface, while renewable energy expansion - particularly solar power - requires vast land areas, often competing directly with agricultural land. This competition has raised concerns regarding land-use conflicts, food security and ecological sustainability. In this context, agrivoltaic farming has emerged as an innovative approach to optimize land productivity by combining agricultural production with solar energy generation.

Agrivoltaic systems were first conceptualized in the early 1980s, but technological and economic constraints limited their adoption. Recent advances in photovoltaic efficiency, declining installation costs and increased emphasis on climate-resilient agriculture have renewed interest in this integrated approach. Agrivoltaic farming aligns with the principles of sustainable intensification, aiming to increase output per unit area while minimizing environmental impacts.

Fig.1. Agrivoltaic farming

Unlike conventional ground-mounted solar farms that exclude agricultural activity, agrivoltaic systems are designed to maintain or enhance agricultural productivity. The partial shading created by solar panels alters microclimatic conditions, which can be beneficial for certain crops, particularly in arid and semi-arid regions. As climate variability intensifies, agrivoltaics offers an adaptive strategy to mitigate heat stress and water scarcity in cropping systems.

Concept and Principles of Agrivoltaic Farming

Agrivoltaic farming is based on the principle of dual land use, where the same parcel of land is used concurrently for agricultural production and photovoltaic electricity generation. The fundamental objective is to maximize overall land productivity, measured as the combined output of crops and energy per unit area. The core principles of agrivoltaic systems include:

1. **Spatial Integration**: Solar panels are installed at a height or spacing that allows sunlight penetration, machinery movement and crop growth beneath or between panel rows.
2. **Optimized Light Sharing**: The system balances light requirements of crops and energy production by adjusting panel tilt, orientation and density.
3. **Microclimate Modification**: Partial shading reduces extreme temperatures, wind speed and soil evaporation, influencing crop physiology.
4. **Sustainable Resource Use**: Improved water-use efficiency and reduced land competition contribute to sustainability goals.

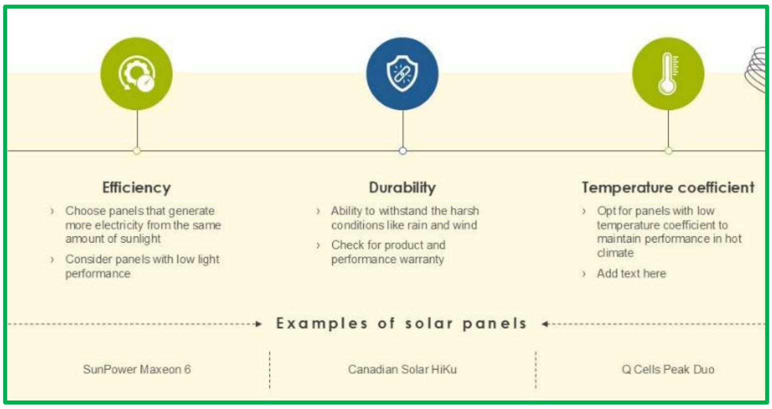

Fig.2. Factors for selection of solar panels

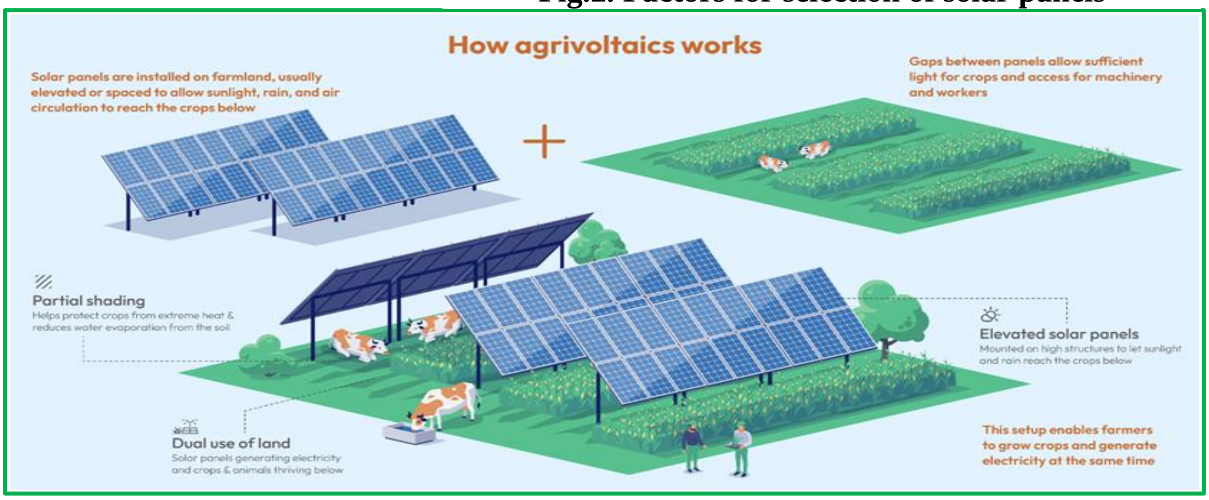

Fig.3. Working of agrivoltaic system

Agrivoltaic designs aim to avoid significant yield penalties while generating substantial renewable energy, thereby improving land equivalent ratios compared to single-use systems.

Types and Design Configurations of Agrivoltaic Systems

The performance of agrivoltaic farming largely depends on system design and structural configuration. Several models have been developed based on crop type, climate and farm scale.

Elevated Agrivoltaic Systems: In elevated systems, solar panels are mounted 3–5 meters above ground level, allowing conventional farming practices such as ploughing, sowing and harvesting. These systems are suitable for field crops, vegetables and fodder crops. Elevated structures minimize shading intensity and facilitate mechanization.

Inter-row Agrivoltaic Systems: In this configuration, solar panels are installed in rows with sufficient spacing between them to cultivate crops in the inter-row areas. This design is commonly adopted in orchards, vineyards and pasturelands. Light availability varies throughout the day, creating alternating sun and shade zones.

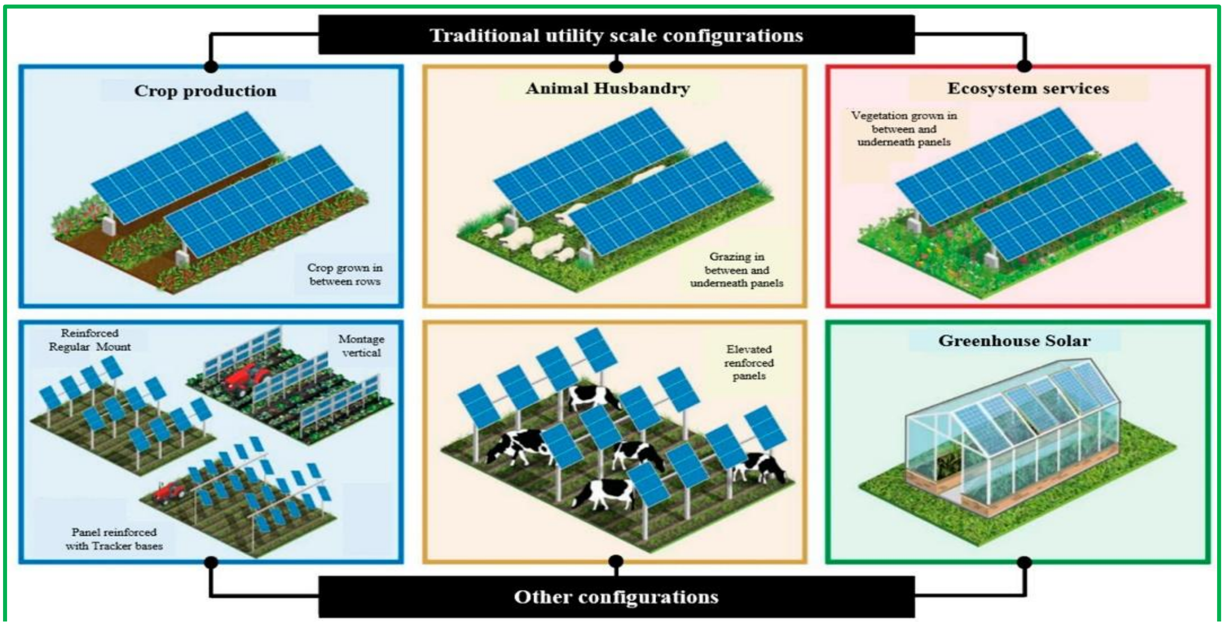

Fig.4. Different configurations of agrivoltaic system

Vertical or Semi-transparent Panels: Vertical bifacial or semi-transparent photovoltaic panels allow diffused light transmission and are particularly useful for horticultural crops and greenhouses. These systems reduce land footprint while maintaining crop productivity.

Mobile and Tracking Agrivoltaic Systems: Solar tracking systems adjust panel orientation according to the sun's position, optimizing energy production and dynamic shading. Although technologically advanced, they require higher investment and maintenance.

Effects of Agrivoltaic Systems on Crop Growth and Productivity

Crop response to agrivoltaic conditions depends on species, variety, growth stage and environmental factors. The partial shading created by solar panels modifies photosynthetically active radiation (PAR), air temperature and soil moisture.

Light Interception and Photosynthesis: Reduced light intensity under panels can lower photosynthesis in light-demanding crops such as maize and wheat. However, shade-tolerant and leafy vegetables such as spinach, lettuce, coriander and amaranthus often exhibit stable or improved growth due to reduced photo-inhibition.

Temperature Regulation: Agrivoltaic shading lowers canopy and soil temperatures by 2–5°C during peak summer periods. This temperature moderation reduces heat stress; delays wilting and improves flowering and fruit set in sensitive crops.

Soil Moisture Conservation: Shaded soil experiences lower evaporation rates, leading to improved soil moisture retention. Studies have reported water savings of 15–30 per cent, making agrivoltaics particularly beneficial in water-limited environments.

Crop Yield Performance: Yield responses under agrivoltaic systems vary:

- **Neutral to positive effects** in leafy vegetables, legumes, forage crops and medicinal plants.
- **Slight yield reductions** in cereal crops, often compensated by improved quality or reduced input costs.

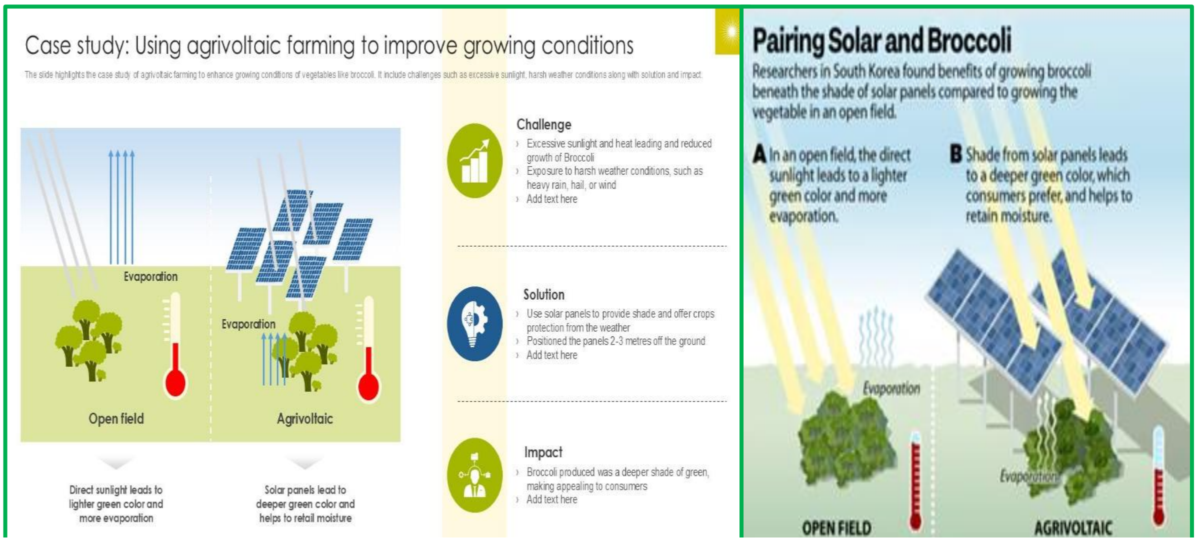

Fig. 5. Effects of Agrivoltaic Systems on Crop Growth and Productivity

Environmental and Ecological Benefits

Agrivoltaic farming contributes to multiple environmental benefits that align with climate-smart agriculture principles.

Climate Change Mitigation: By generating renewable energy, agrivoltaic systems reduce greenhouse gas emissions associated with fossil fuel-based power generation. Simultaneously, improved crop resilience helps farmers adapt to climate variability.

Biodiversity Enhancement: The shaded microhabitats created under panels can support pollinators, beneficial insects and soil organisms. Grasslands under solar panels often exhibit higher plant species diversity compared to conventional monoculture fields.

Reduced Land Degradation: Dual land use reduces the need for land conversion, protecting natural ecosystems and preventing soil erosion associated with large-scale solar installations.

Fig. 6. Environmental and Ecological Benefits

Economic and Social Implications

Improved Farm Income Stability: Agrivoltaic systems provide dual revenue streams from crop production and electricity generation. This diversification reduces financial risk and enhances income stability for farmers.

Employment and Rural Development: Installation, operation and maintenance of agrivoltaic systems create skilled and semi-skilled employment opportunities in rural areas.

Cost Considerations: Initial investment costs are higher than conventional solar systems due to elevated structures. However, long-term returns, government incentives and energy savings can offset these costs.

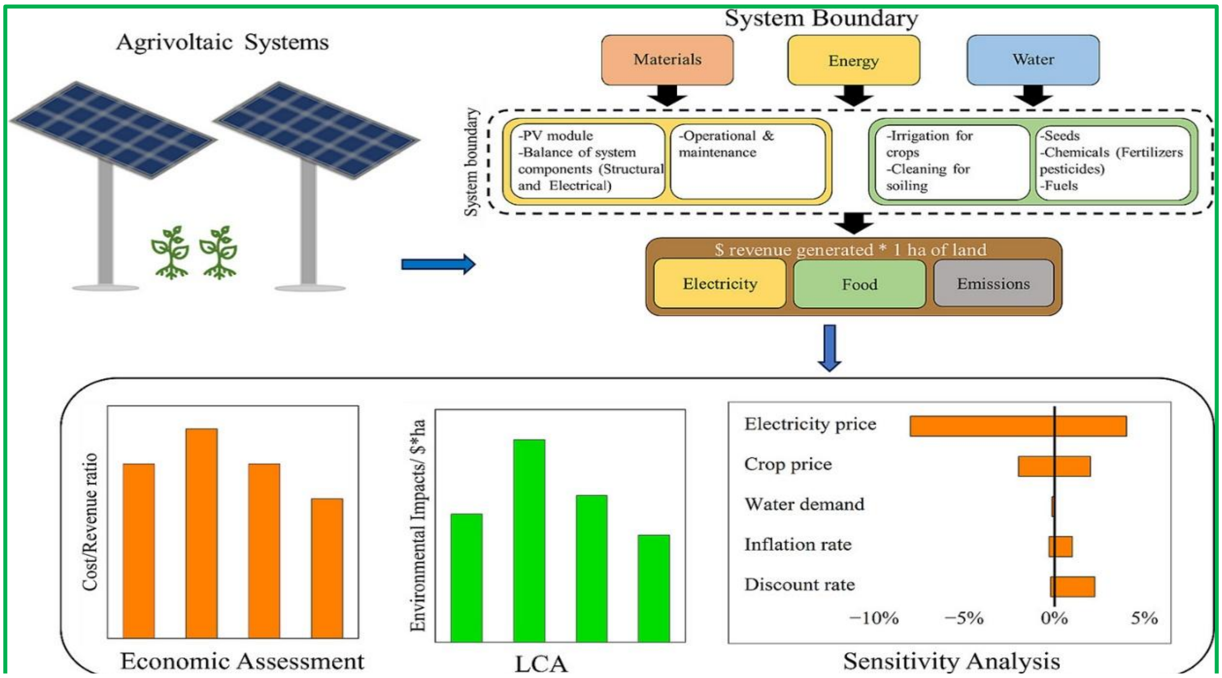

Fig.7. Integrated System Boundary and Sustainability Assessment Framework for Agrivoltaic Systems

Challenges and Limitations

Despite its potential, agrivoltaic farming faces several challenges:

- High initial capital investment
- Complexity in system design and management
- Limited crop-specific recommendations
- Policy and regulatory barriers
- Farmer awareness and technical capacity

Research-based guidelines and supportive policies are essential for large-scale adoption.

Future Prospects and Research Needs

Future agrivoltaic development should focus on:

- Crop-specific light optimization strategies
- Integration with precision agriculture and smart irrigation
- Breeding crop varieties adapted to partial shade
- Long-term ecological impact assessment
- Region-specific economic feasibility studies

Advancements in photovoltaic technology and agronomic research will further enhance system efficiency and adoption.

Schemes and Initiatives Promoting Agrivoltaics in India

India promotes agrivoltaics through national and state-level schemes that integrate solar energy with agriculture, aiming to enhance clean energy generation while increasing farm incomes.

National Initiatives

1. India Agrivoltaics Alliance (IAA): Established by the National Solar Energy Federation of India (NSEFI), the IAA brings together policymakers, solar developers, farmers, financial institutions and researchers. It focuses on developing viable business models, assessing socio-economic impacts and advocating supportive policies to accelerate agrivoltaic adoption across India.

2. PM-KUSUM (Pradhan Mantri Kisan Urja Suraksha Evam Utthan Mahabhiyan) Launched in 2019, PM-KUSUM promotes solar energy use in agriculture through capital subsidies and bank financing. It has three components:

- **Component A:** Grid-connected solar power plants (500 kW–2 MW).
- **Component B:** Standalone solar-powered pumps (up to 7.5 HP) in off-grid areas.
- **Component C:** Solarization of existing grid-connected agricultural pumps.

State-Level Initiatives

1. Mukhyamantri Saur Krushi Vahini Yojana (MSKVY) - Maharashtra: Targets solarization of 1,600 MW agricultural feeders by 2026. Farmers benefit from assured power supply and a fixed tariff of ₹3.10 per kWh, implemented through MSEDCL.

2. Suryashakti Kisan Yojana (SKY) – Gujarat: Provides 60% capital subsidy and loans for installing solar panels on farms. Farmers can sell surplus power at ₹7 per unit for the first 7 years and ₹3.50 per unit for the next 18 years.

3. Surya Raitha Scheme – Karnataka: Encourages solar-powered irrigation pumps with financial assistance. Farmers can export excess electricity to the grid, creating an additional income source.

4. Mukhyamantri Kisan Aay Badhotri Solar Yojana – Delhi: Allows farmers to lease land for solar installations, ensuring a fixed income starting at ₹8,333 per acre per month with a 6% annual increase.

Agrivoltaic Projects in India

India is witnessing a growing number of agrivoltaic projects that integrate solar energy generation with agricultural production. In Sagar, Madhya Pradesh, IIT Roorkee alumnus Anand Jain has developed one of the country's largest agrivoltaic farms over 16 acres, cultivating crops such as strawberries and lettuce beneath elevated solar panels while generating nearly 25,000 units of electricity per day. The project enhances farm income through dual land use; conserves water and protects crops from extreme weather.

In Maharashtra, Sahyadri Farms in Nashik operates a pilot agrivoltaic project combining solar installations with grape cultivation to improve farmer incomes and promote environmentally sustainable practices. The Central Arid Zone Research Institute (CAZRI), Jodhpur, has successfully demonstrated a 105 kWp agrivoltaic system that improved land productivity and water-use efficiency in arid regions, leading to its adoption in similar agro-climatic zones. Additionally, the Muradpur lift irrigation scheme in Nagpur employs floating solar panels to power irrigation across 465 acres, enabling up to three cropping cycles annually while significantly reducing energy costs. Collectively, these initiatives highlight the potential of agrivoltaics to optimize land use, strengthen agricultural resilience and deliver clean energy solutions to Indian farmers.

Conclusion

Agrivoltaic farming represents a scientifically sound and environmentally sustainable approach to address the dual challenges of food security and renewable energy demand. By integrating photovoltaic systems with agricultural production, agrivoltaics enhances land-use efficiency, improves microclimatic conditions, conserves water and supports climate-resilient farming systems. While technical and economic challenges remain, ongoing research, technological innovation and policy support can unlock the full potential of agrivoltaic systems. As global agriculture transitions toward sustainability, agrivoltaic farming is poised to play a significant role in shaping the future of multifunctional landscapes.

References

1. Barron-Gafford, G. A., Pavao-Zuckerman, M. A., Minor, R. L., Sutter, L. F., Barnett-Moreno, I., Blackett, D. T., … Macknick, J. E. (2019). Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands. *Nature Sustainability*, *2*(9), 848–855. https://doi.org/10.1038/s41893-019-0364-5
2. Dupraz, C., Marrou, H., Talbot, G., Dufour, L., Nogier, A., & Ferard, Y. (2011). Combining solar photovoltaic panels and food crops for optimising land use: Towards new agrivoltaic schemes. *Renewable Energy*, *36*(10), 2725–2732. https://doi.org/10.1016/j.renene.2011.03.005
3. Macknick, J., Beatty, B., Hill, G., & Graham, M. (2020). Agrivoltaics: Synergies between solar energy and agriculture. *National Renewable Energy Laboratory Report*, NREL/TP-6A20-76240.
4. Marrou, H., Guilioni, L., Dufour, L., Dupraz, C., & Wery, J. (2013). Microclimate under agrivoltaic systems: Is crop growth rate affected in the partial shade of solar panels? *Agricultural and Forest Meteorology*, *177*, 117–132. https://doi.org/10.1016/j.agrformet.2013.04.012
5. Ravi, S., Macknick, J., Lobell, D. B., Field, C. B., Ganesan, K., & Jain, R. (2016). Colocation opportunities for large solar infrastructures and agriculture in drylands. *Applied Energy*, *165*, 383–392. https://doi.org/10.1016/j.apenergy.2015.12.078