

Agrivoltaics: Growing Crops Under Solar Panels

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Abstract

As the world faces the dual challenge of ensuring food security and meeting rising energy demands, innovative land-use strategies are becoming increasingly important. Agrivoltaics, also known as agrovoltaics, is an emerging approach that integrates agricultural production with solar energy generation on the same piece of land. By installing solar photovoltaic (PV) panels above crops or grazing areas, farmers can simultaneously produce food and renewable electricity. This system not only enhances land-use efficiency but also provides benefits such as reduced water consumption, improved crop resilience under extreme weather conditions, and additional income for farmers. Agrivoltaics has gained global attention as a sustainable solution that addresses climate change, resource scarcity, and rural economic development. This article explores the concept, working principles, benefits, challenges, and future prospects of agrivoltaics in modern agriculture.

Introduction

Agriculture and energy are two sectors that are essential for human survival and economic development. Traditionally, agricultural land has been used exclusively for food production, while separate areas are allocated for energy generation. However, increasing population, urbanization, and climate change have intensified competition for land resources. The need to produce more food while transitioning toward renewable energy has created a pressing demand for innovative land-management solutions. One such solution is agrivoltaics, a system that combines agricultural activities with solar power generation. The term was first introduced in the early 1980s by researchers who envisioned a method to utilize sunlight more efficiently. Instead of choosing between farming and solar energy production, agrivoltaics allows both activities to coexist on the same land.

In an agrivoltaic system, solar panels are mounted at a height sufficient to permit crop cultivation, livestock grazing, or other agricultural operations beneath them. The panels generate electricity while providing partial shade to plants. This unique arrangement creates a microclimate that can benefit certain crops and improve water-use efficiency. With increasing global interest in renewable energy and sustainable agriculture, agrivoltaics is emerging as a promising strategy for maximizing productivity per unit area while supporting environmental conservation.



Fig. 1. Agrivoltaic Farming System

Understanding Agrivoltaics

Agrivoltaics refers to the simultaneous use of land for agricultural production and solar photovoltaic electricity generation. The system is designed to optimize the capture and utilization of solar radiation for both food and energy production. In a conventional solar farm, solar panels occupy large areas of land that may otherwise be used for farming. Agrivoltaic systems overcome this limitation by elevating or spacing solar panels to allow agricultural activities underneath or between them. Depending on the design, agrivoltaic systems can include:

1. **Elevated Solar Panels:** Panels are mounted several meters above the ground, allowing crops and machinery to operate below.
2. **Inter-row Solar Panels:** Panels are arranged with sufficient spacing to permit crop growth between rows.
3. **Movable or Tracking Panels:** Panels adjust their position throughout the day to optimize both electricity generation and sunlight availability for crops.
4. **Greenhouse Agrivoltaics:** Semi-transparent solar panels are integrated into greenhouse structures.

The goal is to achieve a balance between energy production and agricultural productivity without compromising either activity.

How Agrivoltaic Systems Work

Solar panels convert sunlight into electricity through photovoltaic cells. In agrivoltaic systems, only part of the sunlight is intercepted by the panels, while the remaining sunlight reaches the crops below. Many crops do not require full sunlight throughout the day. Excessive solar radiation can increase plant stress, water loss, and soil temperature.

Partial shading provided by solar panels can moderate these conditions. The interaction between crops and solar panels creates a mutually beneficial system:

- Solar panels reduce excessive heat stress on plants.
- Crops and soil release moisture through evapotranspiration, which cools the surrounding air.
- The cooler microclimate can improve the efficiency of solar panels, as photovoltaic cells perform better at lower temperatures.

This synergy can result in higher overall land productivity compared to separate agricultural and solar energy systems.

Benefits of Agrivoltaics

1. Enhanced Land-Use Efficiency

One of the greatest advantages of agrivoltaics is the efficient utilization of land resources. Instead of dedicating land exclusively to either agriculture or energy production, both functions occur simultaneously. Researchers often measure this benefit using the Land Equivalent Ratio (LER), which compares the combined productivity of food and energy production with separate systems. In many cases, agrivoltaic systems achieve significantly higher land-use efficiency.

2. Water Conservation

Water scarcity is becoming a major challenge in agriculture worldwide. Solar panels provide shade that reduces soil evaporation and lowers crop water requirements. The benefits include:

- Reduced irrigation demand
- Improved soil moisture retention
- Enhanced drought resilience
- Better water-use efficiency

These advantages are particularly valuable in arid and semi-arid regions.

3. Improved Crop Performance

Certain crops benefit from partial shading, especially during periods of intense heat and solar radiation. Examples include:

- Lettuce
- Spinach
- Kale
- Cabbage
- Coriander
- Mint

- Turmeric
- Ginger

The moderated microclimate can reduce heat stress, improve photosynthetic efficiency, and enhance crop quality.

4. Additional Income for Farmers

Agrivoltaics provides farmers with a second source of revenue through electricity generation. Electricity may be:

- Used on-farm
- Sold to the grid
- Used for irrigation systems
- Used for cold storage facilities
- Used for processing agricultural products

This diversification reduces financial risk and improves farm profitability.

5. Climate Change Adaptation

Climate change is increasing the frequency of heat waves, droughts, and extreme weather events. Agrivoltaic systems help create a more stable growing environment by reducing temperature extremes and conserving soil moisture. As a result, farms become more resilient to climate-related challenges.

6. Reduction of Greenhouse Gas Emissions

Solar energy replaces fossil-fuel-based electricity generation, reducing carbon emissions. Agrivoltaics therefore contributes to both renewable energy expansion and sustainable agricultural development.

Suitable Crops for Agrivoltaic Systems

Not all crops respond similarly to shaded conditions. Crop selection is a critical factor in the success of agrivoltaic systems.

Highly Suitable Crops

- Leafy vegetables
- Medicinal plants
- Herbs
- Root and tuber crops
- Fodder grasses

Moderately Suitable Crops

- Beans
- Peas
- Potatoes
- Strawberries
- Certain fruit crops

Less Suitable Crops

Some crops requiring intense sunlight throughout their growth cycle may experience reduced yields under excessive shading. Examples include certain cereals and oilseed crops. Therefore, local climate, crop species, and panel design must be carefully considered.

Agrivoltaics and Livestock Farming

Agrivoltaics is not limited to crop cultivation. Livestock production can also benefit from solar installations. Animals such as:

- Sheep
- Goats
- Poultry
- Cattle

can utilize shaded areas beneath solar panels for shelter from heat stress. Benefits include:

- Improved animal welfare
- Reduced heat-related productivity losses
- Natural vegetation control around solar installations
- Reduced maintenance costs

This approach has become increasingly popular in several countries.

Global Progress in Agrivoltaics

Agrivoltaics has gained significant attention worldwide as countries seek innovative solutions to address the growing demands for food, energy, and environmental sustainability. Several nations are actively investing in research, development, and large-scale implementation of agrivoltaic systems. Japan is widely recognized as one of the pioneers in this field, where farmers have successfully adopted elevated solar panel structures that allow crop cultivation beneath them while generating renewable electricity. Germany has emerged as a global leader in agrivoltaic research, conducting extensive studies on crop performance, microclimatic changes, and energy production to optimize dual land-use systems. In France, large-scale agrivoltaic projects are being developed and commercialized to support both sustainable agriculture and national renewable energy targets. The United States is also making significant progress, with universities, research organizations, and commercial farms exploring the use of agrivoltaics for vegetable cultivation, livestock grazing, and the creation of pollinator-friendly habitats around solar installations. Meanwhile, India possesses tremendous potential for agrivoltaic adoption due to its abundant solar resources and vast agricultural landscape. The integration of solar panels

with farming activities can contribute to the country's renewable energy goals, enhance climate resilience, and provide additional income opportunities for farmers. Several states, including Gujarat, Rajasthan, Maharashtra, and Karnataka, are actively exploring agrivoltaic initiatives through pilot projects, research programs, and policy support, highlighting the growing importance of this technology in the future of sustainable agriculture.

Challenges and Limitations

Despite its numerous benefits, agrivoltaics faces several challenges that may hinder its widespread adoption. One of the primary constraints is the high initial investment required for installing elevated solar panel structures, specialized mounting systems, and associated infrastructure, making the technology less accessible to small and marginal farmers. Another challenge is the complexity of system design, as agrivoltaic installations must carefully balance the sunlight needs of crops with the objective of maximizing electricity generation. Improper panel placement or excessive shading can negatively affect crop growth and productivity. Machinery access is also an important consideration, as farm equipment used for planting, cultivation, spraying, and harvesting must be compatible with the height and spacing of the solar panels. Additionally, crop responses to shaded conditions vary considerably; while some crops thrive under partial shade, others may experience reduced yields if the shading level exceeds their optimal light requirements. Furthermore, policy and regulatory issues remain a challenge in many countries, where clear guidelines regarding land-use classification, electricity sales, grid connectivity, incentives, and agricultural subsidies are still evolving. Overcoming these barriers will require continued research, technological innovation, financial support mechanisms, and favorable government policies to ensure the successful integration of agrivoltaics into modern farming systems.

Future Prospects

The future of agrivoltaics is exceptionally promising as advancements in renewable energy technologies and smart farming practices continue to evolve. Innovations in solar technology, artificial intelligence (AI), sensor-based monitoring, and precision agriculture are making agrivoltaic systems more efficient, adaptable, and farmer-friendly. Emerging developments include adjustable solar panels that can change their angle to optimize both electricity generation and crop light exposure, semi-transparent photovoltaic modules that allow a controlled amount of sunlight to reach plants, and AI-driven sunlight optimization systems that dynamically regulate shading based on crop requirements and weather conditions. In addition, smart irrigation systems powered by solar energy can improve water-use efficiency,

while automated monitoring technologies enable real-time assessment of crop growth, soil moisture, microclimatic conditions, and energy production. As countries increasingly focus on renewable energy targets, climate resilience, and sustainable agricultural development, agrivoltaics is expected to become an integral component of climate-smart farming systems. Ongoing research suggests that the simultaneous production of food, water, and energy through agrivoltaic systems can substantially improve resource-use efficiency, enhance farm profitability, strengthen rural livelihoods, and contribute to long-term environmental sustainability.

Conclusion

Agrivoltaics represents a transformative approach to sustainable land management by combining agricultural

production and solar energy generation within the same space. As concerns over food security, climate change, and renewable energy continue to grow, agrivoltaic systems offer a practical and innovative solution. The technology enhances land-use efficiency, conserves water, improves crop resilience, reduces greenhouse gas emissions, and provides additional income opportunities for farmers. Although challenges related to cost, design, and policy remain, ongoing technological advancements and increasing global adoption suggest a bright future for agrivoltaics. By harmonizing food and energy production, agrivoltaics has the potential to become a cornerstone of sustainable agriculture in the twenty-first century.

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