INNOVATIVE STRATEGIES FOR SUSTAINABLE RURAL DEVELOPMENT IN ROMANIA

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RESEARCH ARTICLE

Abstract
In the context of the transition to sustainable agriculture, the use of renewable energy represents a viable solution for reducing operational costs and environmental impact. Photovoltaic panels are increasingly present in Romanian farms, providing economic and ecological benefits, while also posing challenges related to initial investments and their efficient integration into agricultural systems. This study analyzes the impact of photovoltaic panels on Romanian farms, highlighting the advantages and limitations of their implementation. It was found that the cost of electricity, greenhouse gas emissions, and the efficiency of electricity generation vary significantly for each technology, mainly due to differences in technological options as well as the geographical dependence of each renewable energy source. Social impacts were assessed qualitatively based on the major individual effects discussed in the specialized literature. Additionally, the study examined available funding programs for Romanian farmers and current trends in the adoption of renewable energy sources in the agricultural sector. The study showed that farms utilizing photovoltaic panels experienced a significant reduction in energy costs, particularly in areas with high solar exposure. Moreover, initial investments are typically recovered within 5-7 years, depending on farm size and access to subsidies. The main challenges identified include difficulties in accessing financing, lack of energy storage infrastructure, and high costs of advanced technology. However, the large-scale adoption of photovoltaic panels can significantly contribute to the sustainability of Romanian farms, reducing dependence on conventional energy sources and supporting the transition to a greener agricultural economy.

Keywords: photovoltaic panels, renewable energy, sustainability, economy, agrivoltaics systems
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INTRODUCTION

Agriculture requires not only soil tillage and fertilization but also water supply and, in some instances, heating and cooling. These requirements are closely linked to energy consumption, which increasingly relies on electrical power. A viable alternative that has seen a significant price reduction in recent years is photovoltaic energy. This form of energy has rapidly expanded worldwide and has proven to be an effective solution for boosting non-fossil electric power generation. The Europe 2020 strategy on climate change and energy, known as the European 20-20-20 targets, aims to reduce greenhouse gas (GHG) emissions and improve energy efficiency. In addition to this initiative, the United Nations General Assembly declared the period 2014–2024 as the "Decade of Sustainable Energy for All," highlighting the importance of energy issues for sustainable development while encouraging and supporting the broader adoption of renewable energy sources (RES) (Vrînceanu, 2019).

Consequently, within the European Union (EU), the share of RES in gross final energy consumption is expected to rise significantly, from 8.1% in 2005 to 20.6% in 2020 (Bhandari, 2021) as outlined in Directive 2009/28/EC on promoting the use of energy from renewable sources (Bhandari, 2021). However, despite the rapid expansion of solar infrastructure and technologies, the EU market is still undergoing transformation, with an increasing focus on commercial and residential systems that capitalize on reduced solar power production costs, often lower than conventional electricity supply rates. Despite its advantages, photovoltaic panel installation competes with agricultural land use, and in many cases, may displace arable land. Such a trade-off is undesirable both from a production and environmental perspective. To address this challenge, a new concept known as "agrivoltaics" has emerged, which involves land-sharing practices for both crop cultivation and energy generation (Muñoz-García, 2022).

Geographical position, topographic configuration, and climatic characteristics have created favorable conditions for renewable energy exploitation over extensive areas. Situated in the temperate-continental zone, between latitudes 43°40′ and 48°20′, Romania benefits from multiannual average sunshine durations ranging from 1600 to 3200 hours/year and global solar radiation levels between 700 and 1450 kWh/m²/year (3–4 kWh/m²/day), with considerably higher values recorded in plains and plateau regions (2000–2300 hours/year, and 1250–1450 kWh/m²/year). Consequently, photovoltaic farms present themselves as a technology with considerable development potential, especially in low-relief areas (the Danube Floodplain, the Romanian and Banat-Crișana Plains, the Transylvanian Plateau, the Moldavian and Dobrogea Plateaus, and the Getic Piedmont), covering approximately 60% of the country's total area (Vrînceanu, 2019).

Agrivoltaics is an emerging solar energy production approach that combines solar panels with agricultural practices such as crop cultivation, livestock grazing, or pollinator habitats on the same land. By integrating solar panels with alternative land uses, agrivoltaics aims to maximize land efficiency and resource utilization. Solar panels ensure clean energy generation while simultaneously offering benefits such as shade, reduced water evaporation, and moderated temperatures for cultivated plants or animals. This innovative approach promotes both food or biomass production and clean energy generation, fostering a symbiotic relationship between agriculture and solar power that enhances land productivity and contributes to a more resilient and profitable future. Renewable energy systems, particularly photovoltaic (PV) systems, are being adopted to combat climate change and achieve carbon neutrality. However, installing these systems requires large land areas, thereby reducing agricultural land availability. To overcome this challenge, agrivoltaic systems (AVS) are gaining traction, combining solar power production with plant cultivation. AVS enhance land-use efficiency and promote sustainability in agriculture. Initially proposed by Goetzberger and Zastrow, AVS are also referred to as "agrophotovoltaics," "PV agriculture," or "solar sharing." These systems can reduce solar radiation exposure for crops, which may impact plant growth. However, with optimized panel installation, AVS can prevent excessive moisture evaporation while protecting crops from heavy rainfall, snow, or cold winds. Additionally, the generated electricity provides farmers with supplementary income, while water consumption and greenhouse gas emissions are reduced compared to traditional rice fields (Lee, 2023).

Agrivoltaics differs from other solar energy models in that the land beneath and surrounding the solar panels is utilized for additional purposes. In Romania, the most common solar technologies used for buildings are solar photovoltaic panels, which generate electricity and solar thermal systems that heat water or air. PV farms, which prevail in the Romanian Plain, are large-scale photovoltaic systems designed for the supply of merchant power into the electricity grid. Recent worldwide investigations into PV farm implementation in different areas underline their strong connection with environmental changes. These changes are shaped by key driving forces which are natural or biophysical (e.g., sunshine duration) and anthropic (e.g., EU legislative commitments, national legislation, worldwide events, and national and regional economic and political contexts) (Grigorescu, 2019).

A significant percentage is also found in the South-West Development Region, where 63.6% of the panels are located within less than 1 km from the rivers. The South-Muntenia and South-West Development Regions concentrate the largest forest-covered areas; 77.2% of the photovoltaic panels are located within less than 2 km from forests, mainly in Arges, Vâlcea, Prahova, Gorj and Dâmbovița counties (Grigorescu, 2019).

Implementation models of photovoltaic systems in agricultural farms in Romania Grid-Connected Photovoltaic Systems (On-Grid)

These systems are directly connected to the national power grid.

The energy produced is used for the farm's internal consumption, and any surplus is fed into the grid, generating additional income for the farmer through the net metering mechanism or by selling the excess energy produced. These are the most common in the counties of western Romania (Timiș, Arad, Bihor, Caraș-Severin) due to the well-developed electrical infrastructure and easy access to the national power grid.

Farmers in this region frequently use these systems to reduce energy costs and to take advantage of the net metering mechanism, through which surplus energy produced is sold back to the grid. Western Romania benefits from a favorable climate with a long duration of sunshine, which makes these systems highly efficient.

Advantage: Lower installation costs compared to off-grid systems; no need for complex energy storage equipment.

Disadvantage: Total dependence on the grid, meaning that in the event of a power outage, the system cannot supply energy.

Independent Photovoltaic Systems (Off-Grid)

These systems are completely autonomous and typically include batteries for storing the energy produced.

They are ideal for farms located in remote areas without access to the national electricity grid.

Advantage: Total energy independence, ensuring farm operation even in the absence of a power grid.

Disadvantage: Higher initial costs due to batteries and storage equipment.

Hybrid Systems (On-Grid + Off-Grid)

This model combines the advantages of both systems, utilizing both grid power and the energy produced and stored in batteries.

It is an optimal solution for farms seeking to ensure continuity of agricultural activities even during power outages.

Advantage: Provides enhanced energy security and cost optimization.

Disadvantage: Requires larger investments in storage equipment and intelligent energy management systems.

Agrivoltaic Systems (Agrivoltaics)

This model involves integrating photovoltaic panels on agricultural land, allowing simultaneous agricultural activities and energy production.

It may involve installing panels at an elevated height to enable crop cultivation, livestock grazing, or the creation of pollinator habitats beneath the panels. Due to the favorable climate and flat terrain, the western region has high potential for the development of agrivoltaics farms. In western Romania, in Timiș and Arad counties, some agricultural farms have successfully implemented agrivoltaics systems for grapevine and vegetable crops. The results highlighted: A reduction in water consumption for irrigation by up to 25%. An increase in grapevine production by 15% due to the protection provided by the panels against heatwaves and hail. A reduction in energy costs by approximately 40% thanks to self-generated electricity (Mateoc-Sîrb, 2022).

Advantage: Maximizes land use, offering both agricultural production and renewable energy generation.

Disadvantage: Requires careful planning to avoid negative impacts on plant growth.

Mobile or Portable Systems

These are photovoltaic panels mounted on mobile structures that can be relocated based on the farm's needs.

Frequently used to temporarily power agricultural equipment, irrigation pumps, or charging stations for electric machinery.

Advantage: Flexibility in use and adaptation to the farm's requirements.

Disadvantage: Limited energy production capacity compared to fixed systems.

Integrated Systems in farm infrastructure

Photovoltaic panels are installed on the roofs of agricultural buildings (barns, warehouses, stables), reducing the need to occupy productive farmland.

Advantage: Efficiently utilizes space and minimizes energy loss due to proximity to the consumption source.

Disadvantage: Depends on the structure of existing buildings and the capacity of roofs to support the panels.

MATERIAL AND METHOD

To conduct this research, a comprehensive methodology was employed, combining bibliographic analysis, the collection and interpretation of statistical data, as well as graphical analysis and the synthesis of relevant information. The bibliographic analysis was carried out by selecting and evaluating specialized literature from related fields, relevant to the implementation of photovoltaic systems in agriculture. A grouped keyword analysis approach was applied, thus identifying interconnected areas and highlighting the various impacts of these systems on Romanian agriculture. In order to gain a broad perspective on the economic, ecological, and technological impact of these systems, a SWOT analysis was also conducted, which enabled the identification of strengths, weaknesses, opportunities, and threats associated with the implementation of photovoltaic technologies in the agricultural sector. This integrated methodological approach ensured a detailed and well-founded evaluation of the subject, contributing to the formulation of relevant conclusions in both the national and European context.

RESULTS AND DISCUSSIONS

Romanian agriculture, due to its resources, can produce sufficient quantities of agri-food products for domestic consumption, thus limiting imports for basic products (Huang, 2024). However, Romanian farmers face numerous challenges regarding energy consumption, especially in the context of rising energy costs and the need to reduce greenhouse gas emissions (Gillingham, 2018).

The percentage of photovoltaic parks located on fertile arable land: In the South-West and West development regions of Romania, over 65% of photovoltaic parks are located on arable land, of which 63.1% and 42.8%, respectively, overlap with fertile soils (Raportare Științifică, 2021).

The Use of Agrivoltaics Systems – A solution for energy efficiency and sustainability

The implementation of agrivoltaics systems in Romanian farms represents an innovative solution for optimizing land use and reducing dependence on conventional energy sources. Agrivoltaics systems enable the simultaneous production of electricity and agricultural activities, providing both economic and ecological benefits (Vrînceanu, 2019).

The economic impact of agrivoltaics systems in Romanian farms

A comparative analysis between conventional photovoltaic systems and agrivoltaics systems demonstrates the following economic advantages for Romanian farmers the findings, comparing results with previous works and proposing explanation for the result obtained.

Reduction of energy costs – Using solar energy in farms leads to significant savings in electricity consumption, especially for activities such as irrigation, storage of agricultural products, and the operation of agricultural equipment (Udroiu, 2023).

- **Additional income for farmers** – Agrivoltaics systems allow for the production and delivery of surplus energy to the grid, providing farmers with an additional source of income through the net metering mechanism (Udroiu, 2023).
- **Reduction of dependence on conventional energy** – The implementation of agrivoltaics systems reduces farmers' exposure to fluctuations in electricity prices (Mateoc-Sîrb, 2022).

Environmental impact and contribution to sustainability

Agrivoltaics systems significantly contribute to reducing the carbon footprint in agricultural farms by:

- **Reducing water consumption**– Photovoltaic panels provide partial shading, reducing water evaporation and thus protecting crops from drought (Huang, 2024).
- **Protection against extreme weather conditions** – Photovoltaic panels mounted above crops protect plants from hail, heavy rains, and strong winds (Huang, 2024).
- **Increasing biodiversity** – Agrivoltaics systems can contribute to the development of habitats for pollinators and other species beneficial to agriculture (Huang, 2024).

Impact on agricultural productivity

The results of studies conducted in Romanian farms indicate that:

- In farms cultivating grapevines and vegetables**,** agrivoltaics systems contributed to an increase in crop yields by up to 15% due to the protection offered against intense solar radiation and optimized soil moisture (figure 1) (Gheorghiu, 2022).
- Water consumption for irrigation was reduced by up to 25%, thus contributing to efficient water resource management (Gheorghiu, 2022). Reduction of soil moisture evaporation through agrivoltaics systems: The implementation of agrivoltaics systems can reduce soil moisture loss by up to 40%, thanks to the shading provided by solar panels, which contributes to better water retention in the soil (Revista Fermierului, 2025).
- In areas with arid or semi-arid climates, agrivoltaics systems maintained agricultural yield stability and provided better conditions for plant development (Gheorghiu, 2022).

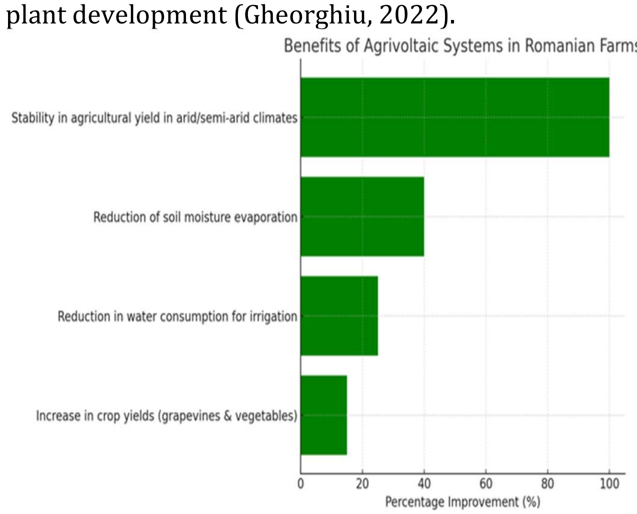

Figure 1 **Benefits of Agriovoltaic Systems in Romania Farms**

Technical and financial viability of agrivoltaic projects in Romania

The implementation of an agrivoltaic system can:

- Reduce total farm electricity costs by approximately 40% (figure 2).
- The payback period for an agrivoltaic system can vary between 5 and 7 years, depending on the size of the farm and access to subsidies or European funds.
- The use of vertically mounted bifacial photovoltaic panels or those with optimized tilt resulted in an increase in energy production by up to 12% compared to conventional systems (Damian, 2024).

	Aspect	Value
1	Reduction in total farm electricity costs	40% reduction
2	Payback period for agrivoltaic systems	5-7 years
3	Increase in energy production with optimized panels	12% increase

Figure 2 **Technical and Financial Viability of Agrivoltaic Projects**

Limiting factors and challenges

Although agrivoltaic systems offer numerous benefits, there are also certain challenges that must be considered:

- **High initial costs** – The initial investment is higher than in the case of conventional photovoltaic systems, especially for support equipment and solar tracking systems (Agrivoltaics alone could surpass EU photovoltaic 2030 goals, 2023).
- **Farm management complexity** – To optimize agrivoltaic performance, farmers must adopt specific agricultural practices to prevent productivity loss in shaded areas (Agrivoltaics alone could surpass EU photovoltaic 2030 goals, 2023).
- **Limited access to financing** – Although there are European support programs for renewable energy, farmers may face bureaucratic challenges in accessing funds (Agrivoltaics alone could surpass EU photovoltaic 2030 goals, 2023).

SWOT Analysis for the implementation of agrivoltaic systems in farms in Romania

STRENGTHS

Dual production on the same land area

Agrivoltaic systems allow efficient land use by enabling the simultaneous production of electricity and agricultural crops. This aspect maximizes farmers' economic returns.

Reduction of energy costs

The implementation of agrivoltaic systems can lead to a reduction of approximately 40% in electricity costs for farms.

Increased agricultural yield

Studies show that agrivoltaic systems can increase the yield of crops such as vineyards and vegetables by up to 15% due to protection against excessive solar radiation and improved soil moisture.

Water resource conservation

Photovoltaic panels provide partial shading, reducing water evaporation and contributing to a reduction of up to 25% in irrigation water consumption.

Reduction of carbon footprint

Agrivoltaic systems contribute to reducing greenhouse gas emissions thanks to the production of clean and renewable energy.

Protection against extreme weather conditions

Photovoltaic panels protect crops from hail, heavy rains, and strong winds, reducing risks to harvests.

Additional sources of income

Through the net metering mechanism, farmers can deliver surplus energy to the grid and generate additional income.

WEAKNESSES

High initial costs

Agrivoltaic systems require a higher initial investment than conventional photovoltaic systems, especially for support equipment and solar tracking technologies.

Complexity of installation and management

The installation and maintenance of these systems are more complex than standard photovoltaic systems. Farmers must adopt specific agricultural practices to avoid productivity loss in shaded areas.

Limited access to financing

Although there are European and national funds for renewable energy projects, farmers may face bureaucratic challenges in accessing them.

Need for technical skills

Farmers may require training to efficiently operate agrivoltaic systems and to effectively manage both agricultural and energy production.

OPPORTUNITIES

Access to European funds and subsidies

The European Union supports the transition to green energy through dedicated funding for the development of renewable energy projects and sustainable agriculture.

Adaptability to various crop types

Agrivoltaic systems can be successfully integrated into farms specializing in vineyards, vegetables, aromatic plants, or crops that require moderate sunlight.

Growing demand for green energy

The increasing interest in renewable energy in Romania offers farmers the opportunity to become producers and suppliers of clean energy.

Sustainability and climate impact reduction

Agrivoltaics contribute to enhancing the resilience of Romanian agriculture in the face of climate change, ensuring crop protection against extreme weather conditions.

Partnership opportunities with energy companies

Farmers can collaborate with solar park developers to implement efficient agrivoltaic systems, thus reducing initial costs.

THREATS

Legislative and economic fluctuations

Changes in energy policies or legislative modifications regarding agricultural land use may influence the viability of agrivoltaic projects.

Risk of reduced productivity for certain crops.

Potential opposition from local communities

In some cases, agrivoltaic projects may face resistance from local communities due to visual impact concerns or fears about land use.

Dependence on weather conditions

Energy yield may vary depending on climatic conditions, which can affect the stability of energy production during certain seasons.

The implementation of agrivoltaic systems in Romanian farms holds significant potential for increasing sustainability and energy efficiency in the agricultural sector. Although there are challenges such as high initial costs and complex management, the economic, ecological, and social benefits justify the adoption of this technology. By leveraging the opportunities offered by European funds and by training farmers to efficiently use these systems, agrivoltaics can become a viable and effective solution for Romanian agriculture (figure 3).

Figure 3 **SWOT Analysis for Agrivoltaic Systems in Farms in Romania**

The integration of photovoltaic systems in the agricultural industry offers multiple benefits, contributing to increased sustainability and energy efficiency. Photovoltaic panels provide the necessary energy for heating greenhouses, giving farmers the opportunity to grow plants throughout the year in an efficient and sustainable manner. These systems reduce dependence on fossil fuels and protect the environment (Figure 4).

Additionally, photovoltaic panels support food preservation by powering refrigeration and freezing units, thus maintaining the freshness of agricultural products and reducing food waste. Using solar energy for these systems leads to significant savings in energy costs (figure 4).

Another major benefit is the ability of photovoltaic panels to power agricultural machinery and irrigation systems, reducing reliance on conventional energy and lowering operating costs. Moreover, these systems can efficiently illuminate greenhouses, storage facilities, and agricultural halls (figure. 4).

Photovoltaic panels also contribute to efficient water use, allowing rainwater collection for irrigation and reducing overall water consumption. Furthermore, the shade provided by the panels reduces evapotranspiration and keeps the soil cooler and more humid, protecting crops during drought periods (figure. 5).

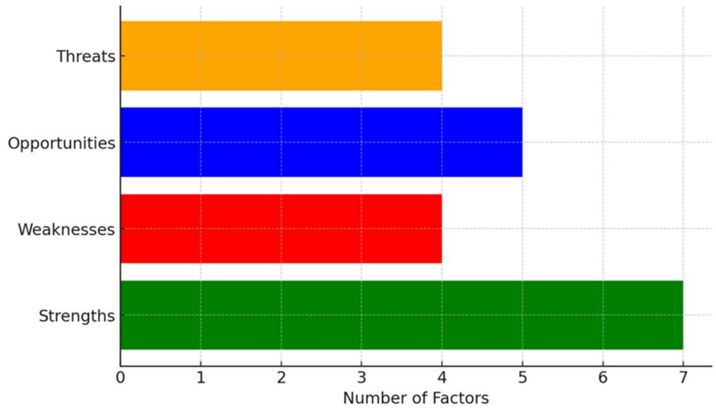

Figure 4 **SWOT Analysis for Agrivoltaic Systems in Farms in Romania**

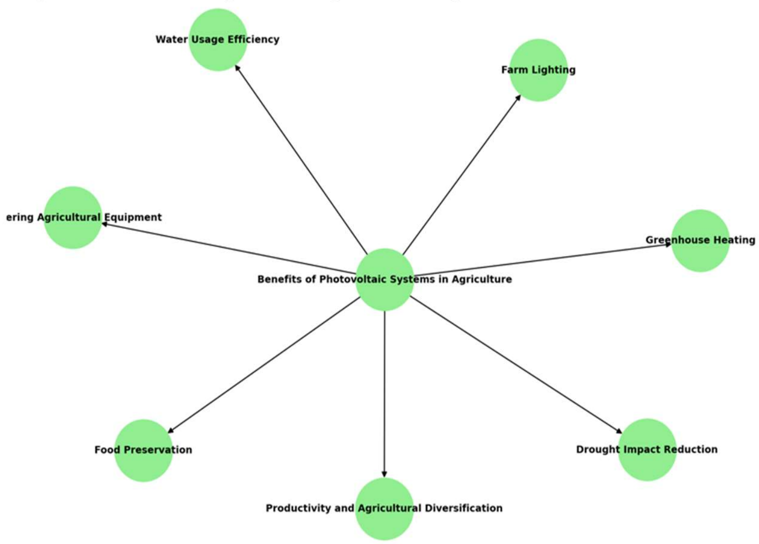

Figure 5 **Diagram of photovoltaic system benefits in agriculture**

CONCLUSIONS

Agrovoltaics and smart agriculture are closely connected. The solar energy generated by panels can meet the energy demands of farms, thus promoting photovoltaic self-consumption. This, in turn, can support the development of smart agricultural technologies such as artificial intelligence, big data, and the interconnection of smart devices. Moreover, integrating agrovoltaics into smart agriculture can lead to increased productivity and optimized resource utilization. The implementation of agrivoltaic systems offers farmers the opportunity to simultaneously produce electricity and agricultural crops on the same land area, thus maximizing income and diversifying agricultural production. Furthermore, the integration of agrovoltaics in smart agriculture presents significant potential for enhancing environmental sustainability. By reducing dependence on conventional energy sources and utilizing renewable solar energy, farms can substantially lower their carbon footprint. This transition to clean energy supports global efforts to mitigate climate change while promoting environmentally conscious farming practices.

Agrovoltaic systems also provide a viable solution to water management challenges. The partial shading created by solar panels reduces soil temperature and minimizes evapotranspiration, contributing to improved soil moisture retention. This is particularly beneficial in arid or drought-prone regions, where water conservation is critical. As a result, farmers can achieve higher crop yields with reduced irrigation requirements, improving resource efficiency.

Additionally, the combination of agrivoltaics with smart agricultural technologies enhances data-driven decision-making. Sensors, IoT devices, and AI-driven platforms can collect and analyze real-time data on weather conditions, soil moisture, and crop health. This enables farmers to implement precision agriculture strategies, optimizing resource allocation, reducing waste, and improving overall productivity.

From an economic perspective, agrivoltaic systems offer long-term financial benefits. While the initial investment may be substantial, the savings on energy costs, combined with potential income from surplus energy fed back into the grid, create a stable financial return. Moreover, the dual-use nature of agrovoltaic systems maximizes land efficiency, allowing farmers to achieve multiple revenue streams from the same plot of land.

In conclusion, integrating agrovoltaic systems with smart agricultural technologies represents a forward-thinking approach that addresses both energy and food security challenges. By leveraging solar energy for sustainable agriculture, farmers can improve productivity, reduce environmental impact, and create resilient farming systems. With continued advancements in technology and increased access to funding opportunities, agrovoltaics has the potential to become a cornerstone of modern, sustainable agriculture.

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