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Agro-Photovoltaics and Food-Energy Security: Evaluating Dual Land-Use Dynamics in Semi-Arid Climates

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ABSTRACT

Agro-photovoltaics (Agri-PV) represents an innovative and sustainable approach to addressing the interconnected challenges of food production, renewable energy generation, and land-use efficiency, particularly in semi-arid climatic regions. Increasing population pressure, climate change, water scarcity, and growing energy demands have intensified the competition for agricultural land and natural resources. Conventional solar photovoltaic installations often require extensive land areas, potentially reducing the availability of land for agricultural activities. Agro-photovoltaic systems offer an alternative by integrating solar panels with agricultural production on the same land, enabling simultaneous electricity generation and crop cultivation. This study evaluates the dual land-use dynamics of agro-photovoltaic systems in semi-arid climates, focusing on their effects on crop productivity, photovoltaic energy generation, water-use efficiency, microclimatic conditions, and overall food-energy security.

The study examines how solar panel height, spacing, tilt angle, shading intensity, and crop selection influence agricultural and energy performance under conditions of high solar radiation, elevated temperatures, and limited water availability. Particular attention is given to the potential of partial shading to reduce soil evaporation, moderate crop canopy temperatures, improve plant water-use efficiency, and protect sensitive crops from excessive solar exposure. Furthermore, the research considers technological, economic, environmental, and institutional factors affecting the adoption of integrated agro-photovoltaic systems. Performance evaluation is proposed through indicators such as Land Equivalent Ratio (LER), crop yield, photovoltaic conversion efficiency, energy productivity, water-use efficiency, and economic returns. The study also highlights the importance of selecting suitable crop varieties and optimizing photovoltaic configurations according to regional climatic conditions.

Keywords: Agro-Photovoltaics, Food-Energy Security, Dual Land Use, Semi-Arid Climates, Sustainable Agriculture.

INTRODUCTION

The increasing global demand for food and energy, combined with climate change, population growth, and environmental degradation, has created significant challenges for sustainable land and resource management. Agricultural systems are under growing pressure to produce sufficient food while maintaining ecological balance and adapting to changing climatic conditions. Simultaneously, the transition toward renewable energy has accelerated the deployment of solar photovoltaic (PV) technologies, which require substantial land areas for large-scale electricity generation. This competition between agricultural production and solar energy infrastructure has raised concerns regarding land-use conflicts, food security, and long-term environmental sustainability. In this context, Agro-Photovoltaics (Agri-PV) has emerged as an innovative approach that integrates agricultural activities with solar electricity generation on the same land.

Agro-photovoltaic systems involve the installation of solar panels above, between, or alongside agricultural crops, allowing the land to perform two productive functions simultaneously. Unlike conventional ground-mounted solar farms, which may replace agricultural activities, Agri-PV systems are specifically designed to maintain crop cultivation while generating renewable electricity. This integrated approach can improve overall land-use efficiency and create opportunities for farmers to diversify their income through agricultural production and energy generation. The concept is particularly relevant in regions where agricultural land is limited, energy demand is increasing, and climatic conditions create additional challenges for crop productivity.

Semi-arid regions represent an especially important application area for agro-photovoltaic technologies. These regions are generally characterized by low and irregular rainfall, high temperatures, intense solar radiation, high evapotranspiration rates, and frequent water shortages. Such environmental conditions negatively affect agricultural

productivity by increasing crop water requirements, reducing soil moisture, and exposing plants to heat stress. Traditional agricultural practices in semi-arid environments often depend heavily on irrigation, making agricultural production vulnerable to groundwater depletion and changing precipitation patterns. The integration of photovoltaic infrastructure with agricultural production may provide an opportunity to address some of these challenges through improved microclimatic conditions and more efficient resource utilization.

PROPOSED MODELS AND METHODOLOGIES

2.1 Research Design and Methodological Framework

The proposed research develops an integrated analytical framework for evaluating agro-photovoltaic (Agri-PV) systems as a dual land-use strategy in semi-arid climatic regions. The methodology focuses on the simultaneous optimization of agricultural productivity, photovoltaic electricity generation, water-use efficiency, and economic sustainability. A multidisciplinary research approach is adopted, combining agricultural science, renewable energy engineering, environmental assessment, and techno-economic analysis.

The proposed framework considers the interaction between climatic conditions, photovoltaic infrastructure, crop characteristics, soil properties, and irrigation requirements. It aims to identify suitable system configurations that maximize combined land productivity while maintaining food production and renewable electricity generation.

2.2 Integrated Agro-Photovoltaic System Model

The integrated Agri-PV model consists of photovoltaic modules installed above or between cultivated agricultural areas. The system allows solar radiation to be distributed between electricity generation and crop photosynthesis.

The major components include:

- Photovoltaic panels: Generate electricity from incident solar radiation.
- Elevated mounting structures: Maintain sufficient clearance for agricultural operations.
- Agricultural cultivation units: Support crop production beneath or between solar panels.
- Irrigation infrastructure: Provides controlled water distribution according to crop requirements.
- Environmental monitoring sensors: Measure temperature, humidity, soil moisture, and solar radiation.
- Energy management system: Monitors electricity production, consumption, storage, and distribution.

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The proposed model compares three major configurations:

1. Conventional agriculture without photovoltaic infrastructure.
2. Conventional ground-mounted solar photovoltaic installations.
3. Integrated agro-photovoltaic systems combining crop cultivation and solar electricity generation.

This comparison helps identify the benefits and limitations of dual land utilization.

2.3 Photovoltaic Energy Generation Model

The photovoltaic energy generation model estimates electricity production under different climatic and installation conditions. Solar energy output depends on solar irradiance, module temperature, panel efficiency, installation orientation, and system losses.
The electricity generation potential can be estimated using:
\[E_{PV}=A_{PV}\times G\times \eta_{PV}\times PR \]
Where:

- \(E_{PV}\) = Photovoltaic energy output.
- \(A_{PV}\) = Total photovoltaic panel area.
- \(G\) = Solar irradiance.
- \(\eta_{PV}\) = Photovoltaic module efficiency.
- \(PR\) = Performance ratio of the photovoltaic system.

The model incorporates seasonal variations in solar radiation and temperature to estimate electricity generation under semi-arid climatic conditions. It also evaluates how panel spacing, tilt angle, orientation, and mounting height influence overall energy performance.

2.4 Crop Productivity and Shading Response Model

The crop productivity model examines the influence of partial shading on agricultural growth and yield. Solar panels modify the amount and distribution of sunlight reaching crops, potentially reducing excessive heat exposure while also limiting photosynthetically active radiation.

Crop performance is evaluated through the following indicators:

- Crop yield per unit cultivated area.
- Plant height and leaf development.
- Photosynthetic activity.
- Soil moisture retention.
- Crop growth duration.
- Water-use efficiency.

The crop yield response can be represented using a simplified relationship:
$$ Y=f(L,T,M,N) $$
Where:

- Y = Crop yield.
- L = Available light intensity.
- T = Crop temperature.
- M = Soil moisture availability.
- N = Nutrient availability.

The model considers different shading levels to determine the suitability of crops for cultivation beneath photovoltaic installations. Crops with moderate shade tolerance and relatively low water requirements may be particularly suitable for semi-arid environments, subject to local field validation.

2.5 Water-Use Efficiency Model

Water scarcity is a major constraint in semi-arid agricultural regions. Therefore, the proposed methodology evaluates the potential of Agri-PV systems to improve water-use efficiency through reduced direct solar exposure and soil evaporation.
Water-use efficiency is calculated as:
$$ WUE=\frac{Y}{ET} $$
Where:

- WUE = Water-use efficiency.
- Y = Crop yield.
- ET = Total crop evapotranspiration.

The methodology compares irrigation requirements, soil moisture levels, evaporation losses, and crop productivity across conventional agricultural plots and Agri-PV plots.
The model also considers the possibility of integrating solar-powered drip irrigation systems to improve water distribution and reduce unnecessary water consumption.

RESULTS & ANALYSIS

3.1 Overview of Agro-Photovoltaic System Performance

The results and analysis of the proposed agro-photovoltaic (Agri-PV) framework focus on evaluating the combined performance of agricultural production and solar electricity generation under semi-arid climatic conditions. The assessment considers crop productivity, photovoltaic energy output, water-use efficiency, microclimatic changes, land-use optimization, and economic feasibility.

The proposed analytical framework compares conventional agricultural systems, standalone photovoltaic installations, and integrated agro-photovoltaic systems. The analysis indicates that combining agricultural production with solar energy generation can improve the overall utilization of available land. However, the extent of improvement depends on photovoltaic panel configuration, crop selection, shading intensity, irrigation management, and local climatic conditions.

The numerical values presented in the following tables are illustrative research scenarios intended to demonstrate the proposed evaluation framework. They should not be interpreted as experimentally measured findings.

3.2 Comparative Analysis of Agricultural Productivity

Agricultural productivity is one of the most important indicators for assessing the effectiveness of agro-photovoltaic systems. Partial shading from photovoltaic panels can influence crop growth by modifying solar radiation, temperature, and soil moisture conditions.

In semi-arid regions, excessive solar radiation and high temperatures may negatively affect crop development. Appropriately designed Agri-PV structures can potentially reduce heat stress and evaporation losses, creating favorable growing conditions for selected crops.

The following illustrative comparison presents potential agricultural performance under different land-use configurations.

Agricultural System	Relative Crop Yield (%)	Soil Moisture Retention (%)
Conventional Agriculture	100	100
Low-Shading Agri-PV	98	108
Moderate-Shading Agri-PV	95	115
High-Shading Agri-PV	78	120

Illustrative Crop Yield Comparison
Relative crop yield under different agricultural configurations; conventional agriculture is normalized to 100%.
0%30%60%90%120%ConventionalLow shadingModerate shadingHigh shading

The comparison suggests that low and moderate shading configurations may maintain relatively high crop productivity, whereas excessive shading can substantially reduce agricultural yield. Although greater shading may improve soil moisture retention, it does not necessarily result in higher crop productivity.

Therefore, the selection of suitable crops and appropriate photovoltaic spacing is essential for maintaining agricultural performance.

3.3 Photovoltaic Energy Generation Analysis

Photovoltaic energy generation is another major performance indicator of integrated Agri-PV systems. Semi-arid regions generally receive substantial solar radiation, creating favorable conditions for solar electricity production.

The proposed model evaluates energy generation according to photovoltaic panel efficiency, installation orientation, temperature, spacing, and shading conditions.

System Configuration	Illustrative Annual Energy Generation (MWh/ha)	Relative Performance (%)
Conventional Agriculture	0	0
Low-Density Agri-PV	450	75
Medium-Density Agri-PV	550	92
High-Density Agri-PV	600	100

Illustrative Annual Electricity Generation
Scenario-based photovoltaic output per hectare of project land, not measured field data.
0 MWh/ha200 MWh/ha400 MWh/ha600 MWh/ha800 MWh/haLow densityMedium densityHigh density
The results indicate that increasing photovoltaic panel density can increase electricity generation per unit of land. However, higher panel density may also increase shading and negatively affect agricultural productivity.

Consequently, the optimal Agri-PV configuration should balance electricity generation with crop growth requirements rather than maximizing photovoltaic capacity independently.

3.4 Water-Use Efficiency and Irrigation Analysis

Water scarcity represents a major limitation to agricultural production in semi-arid climates. Agro-photovoltaic systems may help address this challenge by reducing direct solar exposure and modifying the microclimate surrounding crops.
The proposed framework evaluates water-use efficiency by comparing crop production with the amount of water consumed through evapotranspiration.

\[WUE=\frac{\text{Crop Yield}}{\text{Water Consumption}} \]
The following illustrative scenario demonstrates the potential relationship between photovoltaic shading and irrigation requirements.

Agricultural Configuration	Relative Irrigation Requirement (%)	Relative Water-Use Efficiency (%)
Conventional Agriculture	100	100
Low-Shading Agri-PV	95	103
Moderate-Shading Agri-PV	88	108
High-Shading Agri-PV	82	95

The analysis suggests that moderate shading may reduce irrigation requirements while maintaining comparatively high agricultural productivity. However, excessive shading can reduce crop yield sufficiently to lower overall water-use efficiency.
This finding highlights the importance of integrating photovoltaic infrastructure with efficient irrigation technologies, particularly drip irrigation and soil-moisture-based irrigation scheduling.

3.5 Microclimatic Changes Under Agro-Photovoltaic Systems

Photovoltaic panels can modify the microclimatic conditions of agricultural land by controlling the distribution of incoming solar radiation.

The major environmental parameters evaluated include air temperature, soil temperature, relative humidity, solar radiation, and soil moisture.

Environmental Parameter	Conventional Agriculture	Illustrative Agri-PV Condition
Average daytime air temperature	36°C	34°C
Soil surface temperature	39°C	35°C
Relative humidity	35%	39%
Relative soil moisture	100%	115%
Relative solar radiation	100%	75%

The illustrative results indicate that photovoltaic shading may reduce soil surface temperature and improve soil moisture retention. These changes could provide favorable growing conditions for crops sensitive to excessive heat.

However, the magnitude of microclimatic modification depends on panel height, spacing, wind conditions, season, and local environmental characteristics.

COMPARATIVE ANALYSIS IN TABULAR FORM

The comparative analysis evaluates the performance of conventional agriculture, standalone solar photovoltaic systems, and integrated agro-photovoltaic (Agri-PV) systems under semi-arid climatic conditions. The comparison focuses on agricultural productivity, renewable electricity generation, water-use efficiency, land utilization, microclimatic conditions, economic feasibility, and environmental sustainability.

Table 1. Comparative Evaluation of Different Land-Use Systems

Parameters	Conventional Agriculture	Standalone Solar PV	Agro-Photovoltaics
Primary Purpose	Food production	Electricity generation	Food and energy production
Land Utilization	Single-use	Single-use	Dual-use
Crop Production	High potential	Generally absent	Maintained with suitable design
Electricity Generation	Limited or external	High	Moderate to high
Water Requirements	Moderate to high	Very low for operation	Depends on crop and irrigation
Soil Moisture Conservation	Conventional	Site-dependent	Potentially improved
Microclimate Modification	Limited	Site-dependent	Partial shading effects
Farmer Income	Agricultural revenue	Land lease or energy revenue	Agricultural and energy revenue
Land-Use Efficiency	Conventional baseline	Energy-focused	Potentially higher
Environmental Benefits	Supports food production	Renewable electricity	Combined agricultural and energy benefits

Table 2. Comparative Analysis of Agri-PV Configurations

Performance Indicators	Low-Shading System	Moderate-Shading System	High-Shading System
Crop Yield	98%	95%	78%
Electricity Generation	75%	92%	100%
Soil Moisture Retention	108%	115%	120%
Irrigation Requirement	95%	88%	82%
Water-Use Efficiency	103%	108%	95%
Land Equivalent Ratio	1.73	1.87	1.78
Overall Performance	High	Very high	Crop-dependent

Note: Percentages and LER values are illustrative scenarios, not experimentally validated measurements. Relative values are based on the conventional agricultural baseline or the reference system defined in the Results & Analysis section.

Table 3. Comparative Analysis of Agricultural and Environmental Impacts

Parameters	Conventional Farming	Farming Under Agri-PV	Expected Benefits
Solar Radiation	Full exposure	Partial shading	Reduced excessive radiation
Soil Temperature	Relatively high	Potentially lower	Reduced heat stress
Soil Moisture	Higher evaporation potential	Potentially greater retention	Improved water conservation
Crop Development	Depends on natural conditions	Depends on shading tolerance	Potentially improved crop resilience
Evapotranspiration	Conventional levels	May decrease	Reduced water loss
Heat Stress	Greater exposure	Potentially reduced	Improved microclimatic conditions
Renewable Energy	Not directly generated	Generated simultaneously	Additional energy supply
Climate Resilience	Dependent on conventional adaptation	Potentially enhanced	Improved resource management

Table 4. Comparative Assessment of Economic Feasibility

Economic Indicators	Conventional Agriculture	Standalone Solar PV	Agro-Photovoltaics
Initial Investment	Low to moderate	Moderate to high	High
Operating Cost	Agricultural expenses	Low to moderate	Agricultural and PV maintenance
Revenue Sources	Crop sales	Electricity sales	Crop and electricity sales
Income Diversification	Limited	Energy-based	Multiple income sources
Financial Risk	Agricultural and market risks	Energy market and technical risks	Combined agricultural and energy risks
Payback Period	Depends on crop economics	Depends on electricity economics	Depends on combined revenues
Investment Complexity	Relatively low	Moderate	High
Long-Term Potential	Agricultural sustainability	Renewable energy development	Integrated economic sustainability

Table 5. Comparative Evaluation of Technologies and Applications

Technologies	Major Applications	Advantages	Limitations
Fixed-Tilt Solar Panels	Integrated crop cultivation	Simple installation	Fixed shading patterns
Elevated PV Structures	Agricultural machinery and crop cultivation	Greater farming accessibility	Higher structural costs
Adjustable Solar Panels	Dynamic shading management	Flexible sunlight distribution	Complex operation
Bifacial PV Modules	Electricity generation from front and rear surfaces	Potentially higher energy output	Requires suitable ground and system conditions
Solar-Powered Drip Irrigation	Water-efficient crop production	Improved irrigation management	Installation and maintenance costs
IoT-Based Monitoring	Environmental and crop monitoring	Real-time data collection	Sensor and connectivity requirements
AI-Based Optimization	Energy and agricultural management	Improved decision-making	Requires reliable data and computational resources

4.1 Key Findings from Comparative Analysis

The comparative evaluation highlights several important findings:

1. Improved land-use efficiency: Agro-photovoltaics allows agricultural production and electricity generation to coexist on the same land, potentially reducing competition between food and energy production.

2. Agricultural productivity: Low and moderate shading configurations can maintain relatively high crop yields when suitable crops and panel arrangements are selected.

3. Renewable energy generation: Semi-arid climates provide favorable solar radiation conditions for photovoltaic electricity production.

4. Water conservation: Partial shading may reduce soil evaporation and irrigation requirements, although actual savings depend on crop type and environmental conditions.

5. Economic diversification: Combining agricultural and electricity revenues can create additional income opportunities for farmers.

4.2 Conclusion of Comparative Analysis

The comparative analysis indicates that agro-photovoltaic systems provide a promising alternative to conventional single-purpose land-use systems in semi-arid climatic regions. While conventional agriculture primarily supports food production and standalone photovoltaic installations focus on electricity generation, Agri-PV combines both functions within an integrated framework.

Among the illustrative configurations, moderate shading demonstrates the most balanced performance in terms of crop productivity, electricity generation, water-use efficiency, and Land Equivalent Ratio. However, actual performance must be established through region-specific field experiments and economic assessments.

Therefore, agro-photovoltaics can serve as an important technological pathway for strengthening food-energy security, promoting sustainable land management, and supporting climate-resilient agricultural development in semi-arid environments.

LIMITATIONS & DRAWBACKS

Although agro-photovoltaic (Agri-PV) systems offer significant opportunities for improving land-use efficiency, renewable energy generation, and agricultural sustainability, their implementation in semi-arid climatic regions involves several technical, economic, environmental, and institutional challenges. The integration of photovoltaic infrastructure with agricultural production requires careful planning to ensure that electricity generation does not negatively affect crop productivity and farming operations. The major limitations and drawbacks are discussed below.

5.1 High Initial Investment Costs

One of the primary limitations of agro-photovoltaic systems is their relatively high initial investment requirement. Elevated mounting structures, specialized photovoltaic installations, electrical infrastructure, monitoring equipment, and agricultural modifications increase project development costs.

Small and marginal farmers may face difficulties accessing sufficient financial resources to implement these systems. Although long-term electricity generation and agricultural revenue may improve financial returns, the initial capital requirement can restrict widespread adoption.

5.2 Reduction in Crop Productivity Due to Shading

Photovoltaic panels reduce the amount of direct sunlight reaching agricultural crops. Although partial shading may protect plants from excessive solar radiation and heat stress, excessive shading can negatively affect photosynthesis, plant development, flowering, and crop yield.

Light-demanding crops may experience reduced productivity under high-density photovoltaic installations. Therefore, inappropriate panel spacing and shading intensity can create conflicts between agricultural and energy production objectives.

5.3 Technical Complexity of System Design

Designing an efficient agro-photovoltaic system requires coordination between agricultural requirements and photovoltaic engineering. Panel height, tilt angle, orientation, spacing, structural strength, and shading distribution must be carefully optimized.

The design requirements vary according to crop characteristics, seasonal solar movement, soil conditions, and regional climatic patterns. Inadequate system design may reduce both agricultural productivity and electricity generation.

5.4 Water Management Challenges

Although photovoltaic shading may reduce soil evaporation, it does not automatically guarantee significant water savings. Rainfall interception by solar panels can create uneven water distribution across agricultural plots.

Water may accumulate in certain locations while other areas receive insufficient rainfall. This can create localized moisture variations and increase irrigation management complexity.

Furthermore, semi-arid regions frequently experience groundwater depletion and irregular precipitation, making sustainable irrigation management essential.

5.5 Limited Crop Compatibility

Not all agricultural crops are suitable for cultivation beneath photovoltaic installations. Crop responses depend on light requirements, shade tolerance, growth duration, temperature sensitivity, and seasonal water availability.

Crops requiring high solar radiation may experience reduced yields, whereas selected vegetables, leafy crops, fodder crops, and shade-tolerant varieties may perform more favorably under appropriate conditions.

Therefore, crop selection must be based on regional agricultural conditions and experimental evidence.

CONCLUSION

Agro-photovoltaics (Agri-PV) represents an innovative and sustainable approach to addressing the interconnected challenges of food security, energy security, climate change, and efficient land utilization, particularly in semi-arid climatic regions. The integration of agricultural production with solar photovoltaic electricity generation provides an opportunity to utilize the same land for multiple productive purposes without completely sacrificing agricultural activities. This study, titled "Agro-Photovoltaics and Food-Energy Security: Evaluating Dual Land-Use Dynamics in Semi-Arid Climates," highlights the potential of integrated agricultural and renewable energy systems to support sustainable rural development and improve resource-use efficiency.

The analysis demonstrates that agro-photovoltaic systems can offer several advantages over conventional single-purpose land-use approaches. By providing partial shading, photovoltaic structures may reduce excessive solar radiation, moderate soil temperatures, decrease evaporation losses, and improve soil moisture retention under suitable conditions. These microclimatic modifications can create favorable growing environments for selected shade-tolerant crops, particularly in regions experiencing high temperatures and limited water availability. However, the agricultural benefits depend on appropriate photovoltaic panel spacing, installation height, shading intensity, crop selection, and irrigation management.

The study also emphasizes the importance of optimizing photovoltaic energy generation alongside agricultural productivity. Semi-arid regions generally receive considerable solar radiation, making them suitable locations for renewable electricity generation. Integrating photovoltaic infrastructure with agricultural operations can support irrigation pumps, cold storage facilities, crop processing, and other rural energy requirements. Additionally, surplus electricity may provide farmers with supplementary income through appropriate electricity distribution and purchasing arrangements.

The comparative analysis suggests that moderate-shading agro-photovoltaic configurations may provide a favorable balance between crop productivity, electricity generation, and water-use efficiency. The illustrative Land Equivalent Ratio analysis further demonstrates the potential of dual land utilization to improve combined land productivity compared with separate agricultural and photovoltaic production systems. Nevertheless, these numerical comparisons represent proposed analytical scenarios and require validation through long-term field experiments under actual regional climatic and agricultural conditions.

Despite its considerable potential, widespread adoption of agro-photovoltaic systems faces challenges associated with high initial investment costs, structural requirements, crop compatibility, maintenance, technological complexity, and regulatory uncertainties. Small and marginal farmers may require financial assistance, technical training, and institutional support to implement these systems successfully. Therefore, future development should emphasize affordable photovoltaic technologies, intelligent irrigation management, crop-specific shading optimization, and supportive government policies.

Furthermore, integrating Internet of Things (IoT) sensors, artificial intelligence, remote sensing, and predictive modeling could improve the monitoring and management of agro-photovoltaic installations. These technologies can facilitate real-time assessment of soil moisture, temperature, solar radiation, crop health, and electricity generation, enabling more informed agricultural and energy management decisions.

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