PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol 12(sp1): 01–09
https://doi.org/10.14719/pst.7558

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REVIEW ARTICLE

Agrivoltaic farming: A sustainable approach for climate-smart agriculture

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OPEN ACCESS

ARTICLE HISTORY
Received: 01 February 2025
Accepted: 03 March 2025
Available online
Version 1.0 : 29 March 2025

Check for updates

Additional information
Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

CITE THIS ARTICLE
Santhosh R, Baskaran R, Harisudan C, Prabhaharan J, Bharathi Kumar K. Agrivoltaic farming: A sustainable approach for climate-smart agriculture. Plant Science Today. 2025;12(sp1):01–09. https://doi.org/10.14719/pst.7558

Abstract

Food security in India is increasingly getting threatened by climate change and the growing population. India is working towards achieving net-zero emissions by 2050. Integrating photovoltaics (PV) with agriculture has emerged as a viable option and has given rise to agrivoltaics (AV) which can prove as an innovative solution addressing land competition. Agrivoltaics is a technique that combines solar energy with farming. It offers multiple benefits such as increased agricultural yields, water conservation and reduced greenhouse gas emissions. This paper explores agrivoltaics as a Climate-Smart Agriculture (CSA) approach for Indian farmers and establish a sustainable and reliable model for the future. Agrivoltaics enables dual land use optimizing both food and energy production while mitigating the adverse effects of climate change. It helps improve resource efficiency ensuring a more resilient agricultural system. The potential of agrivoltaics is assessed using Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis. This analysis provides information about its strengths such as land optimization and climate mitigation effects; weaknesses including high initial costs; opportunities, like policy support and technological advancements; and threats, such as land-use conflicts and limited awareness. Implementation of agrivoltaics in Indian agriculture can bring greater sustainability ensuring food security while contributing to clean energy goals. This review emphasizes use of agrivoltaics as a transformative solution for achieving climate resilience and sustainable development in India's agricultural sector.

Keywords

agrivoltaics; climate change; greenhouse gas; SWOT analysis

Introduction

Atmospheric greenhouse gas levels have increased tremendously in the last two million years. Global temperatures have risen by approximately 1.1 °C since the 19th century (1). Global warming, predominantly caused by greenhouse gases is the key factor in climate change. Greenhouse gas (GHG) emissions include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and fluorinated gases. Carbon dioxide accounted for 65 % of global GHG emissions from five major countries (China, United States, India, Russia and Japan) as per recorded in the year 2019 (2). Human activities and population growth are the primary contributors to climate change. Significant greenhouse gas sources include energy production, industrial operations, agricultural practices and waste management. Fossil fuel-based electricity production releases harmful gases like CO_2 into the environment. This gas is mainly responsible for adding excess amount of heat that results in changing weather patterns and increase frequency of floods, severe drought and change the rainfall pattern making the whole planet inhabitable (3). Since climate change is one of the important issues faced by the world today, therefore innovative solutions are required to balance environmental sustainability and human needs.

The demand of energy demand continues to rise with increasing population. Clean and alternative sources of energy are emerging as potential solutions to meet global energy demand. Renewable energy offers a potential solution to these challenges. The renewable energy sources like solar and wind can be used to reduce our dependency on non-renewable energy sources and reduce our carbon footprint.

Projections indicate that the global population will reach 9.8 billion by 2050 (4). Rise in population and climate change exert pressure on agriculture thereby threatening global food and water supplies (5). The United Nations Food and Agriculture Organization (FAO) suggests that food production all over the world must increase by 70 % to sustain increasing the increasing population (6). Various processes such as fertilization, irrigation and mechanization which are involved in agriculture also contribute a lot of greenhouse gases.

Agriculture is considered the foundation of India's economy. According to the 2011 census, 70 % of the population was employed in agriculture, with 47 % directly involved in farm-related occupations (7). Excessive use of fertilizers and pesticides has degraded farmland. The 2019 IPCC report identified land degradation as a driver of climate change and increasing GHG emissions (8).

To mitigate climate change we need to focus on reducing greenhouse gas emissions and enhancing carbon capture. Transitioning to renewable energy sources such as solar, wind and hydropower plays a key role in minimizing reliance on fossil fuels. Sustainable agricultural practices like agrivoltaics, integrate crop cultivation with solar energy production to optimize land use and lower emissions. This paper focuses on integrating solar farming with traditional farming which aligns with Climate-Smart Agriculture's (CSA) objectives. CSA aims to achieve three main goals. The first goal focusses on increasing agricultural productivity that can increase farmers' income, ensure food security and promote rural economic development. Second aims to make farm yields more resilient to natural disasters, pests, diseases and other challenges. Third works for reducing GHG emissions can be reduced by developing technologies applicable to agriculture (9, 10).

One innovative approach to addressing climate change is the adoption of agrivoltaics, a technology that integrates solar panels with agricultural practices to maximize land use efficiency while reducing carbon emissions. Agrivoltaics is the simultaneous use of land for both agriculture and solar energy production. It emerges as a promising strategy to address this dual challenge. By integrating renewable energy generation with food production, agrivoltaics enhances energy efficiency, promotes sustainable land use, reduces carbon emissions and strengthens resilience against climate-related stresses. This innovative approach offers a pathway to harmonize energy and agricultural demands, providing a tangible step toward mitigating the impacts of climate change

Agrivoltaic systems present a viable alternative to fossil fuels. Agrivoltaics (AV) aims to optimize land use for both solar energy production and crop cultivation. This concept was introduced by Goetzberger and Zastrow in 1981. It is an intercropping method used in agriculture developed with an aim to increase land equivalent ratio and total revenue. Cultivating crops under photovoltaic (PV) modules offers economic benefits such as increased revenue and improved land-use productivity. Integration of solar power in agriculture will reduce the efficiency of either solar energy generation or agricultural production, or both, the overall revenue may increase (11, 12). Although there are common concerns that agrivoltaics systems (APV) may hinder plant growth by shading crops with solar panels, but reports have shown that agricultural productivity remains largely unaffected sunlight exceeding the photo saturation threshold does not contribute to the photosynthesis process. Agrivoltaics can be categorized based on the type of agricultural land such as croplands, animal farms and solar greenhouses integrated into agricultural areas. The present review explores the potential of agrivoltaics in climate change mitigation and further assesses the use of technology for achieving agricultural sustainability.

Consequences of climate change

Global climate change encompasses enduring transformations in temperature trends, atmospheric conditions and environmental dynamics primarily resulting from human-driven activities. The combustion of fossil fuels, large-scale deforestation and industrial-scale emissions are key contributors to this phenomenon. These changes are propelled by the accumulation of heat-trapping gases in the Earth's atmosphere including carbon dioxide, methane and nitrous oxide. The far-reaching effects of climate change manifest in diverse ways, impacting biodiversity, human well -being and economic systems worldwide.

In 2024, India experienced extreme weather events on 340 out of 365 days encompassing heat waves, cold waves, cyclones, lightning, heavy rainfall, floods and landslides. These incidents resulted in 3238 fatalities, affected 3.2 million hectares of crops, destroyed 235862 homes and caused the demise of approximately 9457 livestock. Madhya Pradesh encountered extreme weather most frequently, occurring every alternate day. Kerala, however, reported the highest mortality rate at 550, with Madhya Pradesh (353) and Assam (256) following. Andhra Pradesh suffered the most significant housing damage (85806), while Maharashtra, experiencing extreme events on 142 days, accounted for over 60 % of the affected crop area nationwide, followed by Madhya Pradesh (25170 ha). The Central region experienced the highest frequency of extreme events (218 days), followed by the Northwest region (213 days). Regarding casualties, the Central region led to 1001 deaths, followed by the South Peninsula (762 deaths), East and Northeast (741 deaths) and Northwest (734 deaths).

In addition, several climate records have been established for 2024. January was India's ninth driest year since 1901. February exhibited the country's second-highest minimum temperature of 123 yr. May recorded the fourth-highest mean temperature, whereas July, August and September all registered their highest minimum temperatures since 1901. In the Northwest, January was the second driest and July experienced the region's second-highest minimum temperature. The South Peninsula endured its warmest February on record, followed by exceptionally warm and dry March and April, but received a 36.5 % surplus in July rainfall and the second-highest minimum temperature in August. (Table 1) below offers a detailed summary of the consequences of climate change, organized by key areas of impact. Each category highlights specific challenges resulting from climate shifts, showcasing the extensive effects on the environment, ecosystems, human communities and the global economy. This overview emphasizes the interconnectedness of climate-related issues and stresses the pressing need for coordinated and sustainable actions to address them.

Agrivoltaics

Agrivoltaics optimizes land use by integrating solar panels with crops (Fig. 1). The idea of agro-photovoltaics (APV) was initially conceived by Goetzberger and Zastrow in 1982 to modify solar power installations to allow simultaneous crop cultivation in the same area (13). For the technology, solar collectors were elevated 2 m above ground level and gaps were increased in the gaps between them to prevent excessive crop shading. These systems would require only one-third of the incoming solar radiation (14). It took approximately 30 years for this concept to be referred to as agrophotovoltaic, agroPV, agrivoltaic, or solar sharing. By generating both solar energy and agricultural products in a single location, it is possible to share light, enhance freshness and decrease moisture loss. The integration of solar technology with agriculture began in 1975 with the development of the first photovoltaic water pump (15).

Table 1. Consequences of climate change

Category	Consequences
Environment	•Rising global temperatures •Melting glaciers and polar ice •Rising sea levels
Weather Patterns	•Increased frequency of extreme weather events •More intense hurricanes •Severe droughts
Ecosystems	•Loss of biodiversity •Habitat destruction •Ocean acidification
Agriculture	•Decreased crop yields in some regions •Changes in growing seasons •Soil degradation
Water Resources	•Water scarcity in arid regions •Increased risk of flooding •Changes in freshwater quality
Human Health	•Spread of diseases like malaria •Heat-related illnesses •Food and water insecurity
Economic	•Increased disaster recovery costs •Disruption of industries •Damage to infrastructure
Social Impacts	•Climate-related migration •Displacement of communities •Increased inequality

Fig. 1. Agrivoltaic system integrating solar panels with crop cultivation.

Global status of agrivoltaics

Agrivoltaic (AV) system categorized under agricultural 5.0 present a potential solution to the meet the growing needs of food and energy. These systems utilize power resources to support agricultural production, encompassing facility gardening, breeding and specialized pastoral structures thereby establishing a novel production model that integrates farming, power generation and agricultural activities (16). Research on solar energy applications in agriculture commenced as early as the 1960s in countries such as Britain, France, India, Portugal and the United States. The emergence photovoltaic technology gradually drew attention toward agrivoltaic applications (17).

The introduction of the first photovoltaic water pump in 1975 marked the inception of integrating photovoltaic technology with agriculture. However, this concept remained largely unexplored until 2004 when Akira Nagashima constructed the first system in Japan designating it as "solar sharing" (18). Subsequently AVS proliferated across Europe, Asia and the United States, ranging from small-scale family farming operations to extensive installations exceeding 700 MW in China, offering diverse benefits to farmers globally. China initiated large-scale agrivoltaic systems in 2014 and continues to maintain global leadership in installed capacity (19). France became the first European nation to support agrivoltaics, implementing regular tenders in 2017 systematically. By 2021 agrivoltaics had evolved into a market-ready technology with a global installed capacity surpassing 14 GWp (20).

Current status of agrivoltaics in India

India ranks as the third-largest contributor to greenhouse gas emissions (21). The intensification of climate change, primarily attributed to anthropogenic activities such as the combustion of fossil fuels, has exacerbated global warming, resulting in a continuous increase in earth's temperatures (22).

Agrivoltaics that represents concurrent use of land for agriculture and photovoltaic (PV) power generation is gaining traction in India as a sustainable solution to land-use challenges and energy needs. Despite offering dual advantages in energy and food production APV has not yet achieved widespread implementation in India. The country's initial APV project was initiated in Gujarat in 2012 and India continues to conduct pilot projects (23). According to a report from the National Solar Energy Federation of India (NSEFI), an advocacy organization a minimum of 22 APV projects were operational across various regions of the country by July 2023. These projects vary in design and capacity reflecting the country's commitment to exploring diverse agrivoltaic models. Notably 1.4 MW agrivoltaic project in Parbhani, Maharashtra has been operational for over a year demonstrating the practical viability of such systems.

The Pradhan Mantri Kisan Urja Suraksha evam Utthan Mahabhiyan (PM-KUSUM) scheme plays a pivotal role in promoting agrivoltaics. This program offers up to 60 % subsidies from the central government supplemented by state support and loans making solar energy more accessible to farmers. It encourages the installation of solar pumps and grid -connected solar power plants on agricultural lands, enabling farmers to generate income by selling surplus power. Agrivoltaics, which involves the simultaneous utilization of land for agricultural purposes and photovoltaic (PV) power generation, presents a potential solution for the future competition between agriculture and renewable energy over land resources in India (24).

The role of agrivoltaics in advancing climate-smart agriculture

Agrivoltaic systems as emerged as an innovative and sustainable technology in response to escalating climate change, dwindling resources and increasing energy needs. These systems involve installing photovoltaic (PV) panels on agricultural land, enabling concurrent solar energy production and crop cultivation. Agrivoltaics systems optimize land utilization by combining energy generation and agriculture on a single plot. This dual-purpose approach mitigates the necessity for additional land conversion and attenuates the environmental impact (25). Some of the points highlighting the importance of the Agrivoltaics systems are listed below.

1. The shade provided by solar panels can reduce soil and water evaporation, resulting in more efficient water utilization in agriculture. This is particularly advantageous in arid and semi-arid regions with scarce water resources (26).
2. By producing renewable energy, agrivoltaics systems decrease dependence on fossil fuels and reduce greenhouse gas emissions. This contributes to mitigating climate change and its effects on agriculture and ecosystems (27).
3. The vegetation growing beneath and around solar panels can enhance carbon sequestration in soil and biomass, further reducing atmospheric CO_2 levels (28).
4. Solar panels can assist in minimizing soil erosion by shielding the soil surface from wind and water. This helps to preserve the soil structure and prevents the loss of valuable topsoil (29).
5. Agrivoltaic systems can establish microhabitats that support the local flora and fauna. The solar panels and associated infrastructure can provide shelter and resources for various species (30).
6. Enhanced soil health and decreased evaporation can lead to reduced need for chemical inputs such as pesticides and fertilizers. This can mitigate the environmental impact of agricultural practices and diminish the risk of runoff pollution.
7. The shading effect of solar panels can help crops withstand extreme weather conditions, such as heat waves and intense solar radiation, by moderating temperature extremes. This can enhance the resilience of agricultural systems to climate variability and severe weather events (31).

The role of agrivoltaic systems in sustainable land use management

Agricultural lands offer ideal opportunities for dual land use, where solar panels can be strategically placed to generate energy while enabling continued agricultural productivity. Agrivoltaics not only enhances land use efficiency improving overall productivity by 60-70 % but also increases crop yields and promotes the potential for renewable energy production (32, 33).

One key performance indicator used to compare AV systems is the land equivalent ratio (LER). Land Equivalent Ratios (LERs) are indicators of the productivity of the land used to assess the value of mixed cropping systems (34). The concept of the Land Equivalent Ratio can be extended to any system that mixes two (or more) types of production on the same land unit and we propose here to apply this concept to the suggested new agrivoltaic systems. The LER of an agrivoltaic system is defined as:

$$LER = (YcropingAV/Ymonocrop)+(YelectrictyAV/YelectricityPV) \quad \text{(Eqn.1)}$$

Where the monocropping system refers to the sole cropping of the crop; PV refers to a standard PV plant and AV refers to the mixed agrivoltaic system. Agrivoltaics optimizes land use by combining both activities on the same piece of land. This minimizes the need for additional land conversion and reduces the impact on natural habitats and ecosystems. As agrivoltaics rely on renewable energy, the adoption supports global efforts to combat climate change as the systems contribute to GHG emissions reduction.

The role of agrivoltaic systems in reducing carbon footprint

Agrivoltaics is an integrated system that combines agricultural practices such as crop cultivation, livestock breeding and aquaculture with solar power generation. This system can produce additional electricity, reducing dependence on coal-based power plants. These systems enable clean power generation above the panels and efficient agricultural production beneath them without altering the atmosphere. These systems can promote sustainable agriculture and reduce greenhouse gas emissions. The International Energy Agency (IEA) states that photovoltaic plants produce no greenhouse gases or air pollutants during operation (35). Furthermore, farmers rely on livestock for supplementary income and farm work. Each liter of fresh milk purchased is responsible for approximately 3 kilograms of greenhouse emissions (36). Of particular concern, the greenhouse gases produced by livestock primarily consist of methane, which is considered more detrimental to global warming due to its higher infrared absorption compared to CO_2 (37). Agrivoltaics, as a secondary income source, could decrease farmers' dependence on livestock, thereby reducing excessive methane production. Transitioning from conventional electricity generation methods to photovoltaics will directly lower greenhouse gas emissions.

Impact of solar panel shading in agrivoltaic systems

Agrivoltaic systems contribute directly and indirectly to reducing greenhouse gas (GHG) emissions, primarily through the shading effects of solar panels. Agrivoltaic systems, which involve partially shading or covering the soil with photovoltaic (PV) modules, help to retain soil moisture and enhance its water-holding capacity. By reducing soil temperatures, these systems contribute to creating a more favorable environment for plant growth (38). Cooler soil temperatures help stabilize microbial processes, leading to a reduction in nitrous oxide (N_2O) emissions. Large-scale PV power generation is essential for mitigating climate change and agrivoltaics is emerging as a sustainable alternative energy source. It optimizes multifunctional land use by supporting both electricity generation and agricultural activities simultaneously (39). Additionally, the partial shade provided by agrivoltaic systems has been shown to benefit crop water balance and reduce evapotranspiration. The shading effects also support a broader range of plant and animal species, while cultivation practices under agrivoltaic systems further enhance soil quality

According to (40) Studies have shown that a shading threshold of around 25 % is generally suitable for maintaining good crop yield and quality in both open fields and greenhouses with photovoltaic integration. This highlights the importance of selecting shade-tolerant crops for AV farming, such as vegetables like lettuce, spinach and herbs.

According to one study where the experimental farm of area 100 m^2 and was divided into three sub-configurations: no modules (control), low module density and high module density (41). The results showed that fresh weight, biomass and yield of corn were higher in the low-density configuration as compared to both the high-density configuration and the no-module control configuration (Table 2). The results indicated that corn yield is influenced by shading. This is because shading affects the amount of incident solar irradiation, which in turn impacts the weight of the crops, the biomass of the plants and overall yield.

Impact of water conservation on sustainable agriculture

Water scarcity is an increasingly critical issue in many parts of the world and is expected to worsen due to population growth and climate change (42). Agrivoltaics (APV) offer a promising solution by reducing crop evapotranspiration water loss from soil evaporation and plant transpiration during photosynthesis through the shading effect of solar panels. This leads to significant water savings, particularly in arid and semi-arid regions, thereby enhancing agricultural resilience to droughts (43).

Advances in agrivoltaic technology have further improved its efficiency and competitiveness. For instance, present novel system combines concentrator photovoltaics (CPV) with diffractive thin-film interference technology (44). This innovative system enables dual use of land for plant growth and electricity generation in a highly efficient manner. By leveraging dichroic polymer films, sunlight is separated into two parts: one optimized for efficient plant growth and the other for solar power generation. This approach is both cost-effective and advantageous compared to traditional solar panels. Research shows that vegetables grown under the polymer films such as lettuce, cabbage and cucumber grow faster, yield better quality and exhibit improved photosynthetic indices compared to control plants without film coverings (45).

Additionally, these multilayer polymer films, when combined with curved glass coverings, significantly reduce water evaporation from farmland by blocking near-infrared (NIR) and far-infrared (FIR) radiation. This not only conserves water but also improves plant growth conditions (32). The use of such advanced film technology in agrivoltaics results in superior crop yield and quality, making it a competitive and sustainable solution for future agriculture in water-scarce regions. It was noticed that water losses through evapotranspiration was decreased in the partial shade of the AV facility (12).

Impact of agrivoltaic systems on microclimate modifications

Microclimate refers to localized climate conditions within a small area, influenced by factors such as topography,

Table 2. Comparison of average fresh weight, biomass and yield of different crops under various agrivoltaic (AV) configurations

Crops	Particulars	Configurations		
		Control	Low density	High density
Corn	Average fresh weight (g)	372.2	393.0	358.8
	Average biomass (kg/m²)	1.63	1.71	1.58
	Yield (kg/m²)	3.35	3.54	3.23
Wheat	Average fresh weight (g)	530.1	548.3	515.6
	Average biomass (kg/m²)	1.80	1.89	1.74
	Yield (kg/m²)	4.20	4.31	4.10
Potato	Average fresh weight (g)	410.5	425.7	398.3
	Average biomass (kg/m²)	2.10	2.24	2.00
	Yield (kg/m²)	5.80	6.05	5.60
Alfalfa	Average fresh weight (g)	320.3	338.6	310.9
	Average biomass (kg/m²)	1.35	1.42	1.30
	Yield (kg/m²)	2.85	2.96	2.78

vegetation and human-built structures like solar panels. Unlike regional climates, microclimatic variations can be significant even over short distances. Agrivoltaic systems (AVS) play a crucial role in mitigating the impacts of climate change by improving microclimatic conditions (46). Solar panels in AVS act as a canopy, protecting crops from direct sunlight and excessive rainfall, which helps regulate temperatures and evaporation. This creates a more favourable environment for crop growth while ensuring sufficient water availability to maximize yields and enhance food security, especially in water scarce regions (47).

The shading effect of solar panels reduces solar radiation on the ground, leading to decreased soil and ambient air temperatures. This creates a cooler relatively moist microclimate that supports crop growth and improve solar PV panel efficiency indirectly. Specifically, the reduction in ambient air temperature beneath the panels can lower panel temperatures by 1-2 ^{0}C, thereby increasing the energy efficiency of the photovoltaic system.

Moreover, agrivoltaics positively influences water management by reducing evaporation and transpiration rates, which conserves water and reduces irrigation demands. Studies have shown that AV systems not only protect crops from extreme irradiation effects, such as sunburn and heat stress, but also enhance water availability (48). The improved microclimatic conditions resulting from AV systems optimize crop productivity, water use and energy generation, making them an effective solution for sustainable agriculture in regions facing climate and water challenges.

According to some studies soil temperature showed reduction by 1.2 ^{0}C in 2017 and 1.4 ^{0}C in 2018 (49). This is in accordance with other findings where the soil temperature reduced under AV (50). In 2017, yearly mean soil moisture was 1.9 % higher under AV, while it decreased by about 3.1 % in 2018. In both years, mean air humidity was 2.8 % higher in AV as compared to REF. No differences between the treatments were found in yearly mean air temperature (Table 3).

Analysis of SWOT in the integration of solar farming with agricultural practices

SWOT analysis is a widely recognized strategic management tool that proves valuable in supporting strategic decisions by systematically evaluating both internal and external system characteristics (51, 52). Internal factors are categorized as strengths (S) and weaknesses (W) in comparison to competing systems, while external factors encompass opportunities (O) and threats (T) within the environment affecting the system (53). Through qualitative assessment and strategic understanding of situations, decision-makers can evaluate measures to leverage strengths, address weaknesses, capitalize on opportunities and mitigate threats (54). Fig. 2 illustrates the factors that may impede the widespread adoption of agrivoltaics.

Fig. 2. Swot analysis.

Strengths

1. Dual land use: Enables simultaneous use of land for agriculture and solar energy production, maximizing resource efficiency (55).
2. Energy generation: Provides renewable energy, contributing to energy security and reducing carbon footprints (56).
3. Crop benefits: Solar panels provide shade, reducing heat stress on crops and minimizing water evaporation.
4. Economic diversification: Farmers can diversify income sources by leasing land for solar installations or selling generated electricity (57).
5. Microclimate creation: Panels create a microclimate that might improve yields for shade-tolerant crops.
6. Water use efficiency: Reduced evaporation under panels leads to improved water management for irrigation.
7. Policy support: Increasing global recognition and policy incentives for sustainable land-use solutions.

Weakness

1. Initial costs: High capital investment is required for setting up solar infrastructure.
2. Technical challenges: Proper alignment, spacing and panel height are critical to avoid negative impacts on crops.
3. Maintenance complexity: Managing both energy infrastructure and agricultural operations simultaneously increases operational complexity.
4. Crop limitations: Not all crops are suitable for partial shading; some may experience reduced yields (13).

Table 3. Yearly averages of air, temperature, humidity, soil temperature and soil moisture under the agrivoltaic system (AV) and the reference site (REF) in 2021, 2023 and 2024

Year	Study location	Crop type	Air, temperature change (AV vs. REF)	Humidity change (AV vs. REF)	Soil temperature change (AV vs. REF)	Soil moisture change (AV vs. REF)	Source
2021	Germany	Winter wheat, Potato, Grass–clover	Not specified	Not specified	Decreased under AV	Increased under AV	(63)
2023	France	Alfalfa	Decrease of ~5 °C during heatwaves	Not specified	Not specified	Not specified	(64)
2024	Sweden	Various	Significant variations observed	Not specified	Not specified	Not specified	(65)

5. Land use conflicts: Stakeholders may prioritize one use (energy vs. agriculture) over the other, leading to potential conflicts.
6. Knowledge gaps: Limited awareness or technical expertise among farmers about agrivoltaic systems (58).

Opportunities

1. Climate resilience: Enhances resilience against extreme weather conditions by protecting crops and diversifying energy resources.
2. Innovation potential: Advancements in semi-transparent or adjustable solar panels could optimize energy and crop yields.
3. Policy and funding: Governments and organizations are increasingly offering incentives and grants for renewable energy and sustainable agriculture.
4. Market growth: Growing demand for sustainable and renewable energy solutions presents a huge market opportunity.
5. Research collaboration: Universities and private sectors are investing in optimizing agrivoltaic technologies.
6. Carbon credits: Agrivoltaic projects can qualify for carbon offset credits, offering additional revenue streams.

Threats

1. Global scalability: Viable for regions with high solar irradiance and arable land, especially in water scarce or developing areas.
2. Regulatory barriers: Policies on land use and renewable energy vary and may limit large scale adoption.
3. Market fluctuations: Energy market volatility and changes in crop prices could affect profitability
4. Social resistance: Community concerns about visual impacts or potential loss of agricultural heritage may hinder adoption
5. Climate risks: Extreme weather (hail, storms) could damage solar infrastructure or crops.
6. Technology risk: Dependence on technology might pose risks if systems fail or become outdated.
7. Land scarcity: Competing demands for land in densely populated areas might limit feasibility (59).
8. Biodiversity concerns: Poorly designed systems could disrupt local ecosystems or wildlife habitats.

Significance of SWOT analysis

The SWOT analysis serves as a strategic tool to systematically assess the Strengths, Weaknesses, Opportunities and Threats associated with agrivoltaic systems. This approach helps in identifying key advantages such as improved land-use efficiency and renewable energy generation, while also addressing potential challenges like high initial costs and shading effects on crops. Moreover, it highlights external opportunities, such as policy support and technological advancements and threats, including climate variability and economic constraints.

By conducting this analysis, decision-makers can formulate informed strategies to enhance the feasibility and scalability of agrivoltaic systems. The revised section now provides a more detailed discussion on the strategic importance of SWOT analysis in optimizing the benefits and overcoming the limitations of agrivoltaics (60).

Conclusion

Agrivoltaics offers an innovative and promising approach to addressing the twin challenges of food security and sustainable energy production in the context of climate change. This method combines photovoltaic technology with agricultural practices, maximizing land utilization, reducing water consumption and improving crop resilience under changing environmental conditions. The system's ability to mitigate extreme temperatures, minimize evaporation and generate renewable energy underscores its significance as a climate-smart farming technique. Despite its vast potential, the widespread implementation of agrivoltaics faces challenges such as high technological costs, location-specific variations and the need for tailored solutions to accommodate diverse crops and climates. Advancing this approach on a global scale will require further research, supportive policies and collaboration among farmers, researchers and policymakers. By promoting sustainable food production and clean energy generation, agrivoltaics paves the way for a more resilient and environmentally conscious agricultural sector, contributing significantly to global climate adaptation and mitigation goals.

Acknowledgements

We extend our sincere thanks to the Tamil Nadu Agricultural University in Coimbatore and the Agricultural College and Research Institute located in Madurai for providing essential technical assistance and expert advice.

Authors' contributions

The first draft of the manuscript was written by SR. BR provided guidance for overall correction and improvement. HC, PJ and BK assisted with literature collection and formatting. All authors contributed equally to revising the manuscript and approved the final draft.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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