Transparent and semi-transparent photovoltaic panels in agrivoltaic systems: enhancing sustainable agriculture and renewable energy production

Alexandra M. Chețan, Alexandra I. Ciolpan, Robert A. Kudor

Department of Environmental Engineering and Protection, Faculty of Agriculture, University of Agricultural Sciences and Veterinary Medicine of Cluj-Napoca, Cluj-Napoca, Romania. Corresponding author: A. I. Ciolpan, alexandra-ioana.ciolpan@student.usamvcluj.ro

Abstract. The increasing demand for renewable energy and sustainable food production has intensified competition for land resources, highlighting the need for integrated solutions that address both challenges simultaneously. Agrivoltaic systems, particularly those based on semi-transparent photovoltaic panels, represent an innovative approach that enables the dual use of agricultural land for electricity generation and crop cultivation. This paper examines the role of semi-transparent photovoltaic panels in modern agriculture, comparing their performance with traditional opaque panels and evaluating their agronomic, environmental, and economic impacts. Semi-transparent photovoltaic panels allow partial transmission of solar radiation, ensuring adequate photosynthetically active radiation for crops while converting the remaining sunlight into electrical energy. The study highlights how these systems improve land-use efficiency, regulate microclimatic conditions, reduce soil water evaporation, and enhance water-use efficiency, especially in regions affected by high temperatures and water scarcity. Case studies and field experiments demonstrate that shade-tolerant and high-value crops such as lettuce, spinach, and tomatoes can maintain or even increase yields under semi-transparent panels, while benefiting from reduced heat stress and irrigation requirements. In addition to agronomic benefits, agrivoltaic systems offer economic advantages by providing farmers with dual income streams from agricultural production and on-site renewable energy generation. Despite challenges related to high initial investment costs, technical optimization, and regulatory frameworks, ongoing technological advancements and supportive policies are expected to improve system viability. Overall, semi-transparent agrivoltaic systems represent a promising and sustainable solution for enhancing food security, renewable energy production, and climate resilience in agricultural landscapes.
Key Words: agrivoltaic systems, land-use efficiency, microclimate regulation, renewable energy, sustainable agriculture, water-use efficiency.

Introduction. Fossil fuel-based energy sources are causing detrimental environmental issues such as global warming and climate change. The greenhouse gas emission into the atmosphere from power generation has increased exponentially in the past few decades. At the same time, agriculture faces mounting challenges due to the growing global population, increased demand for food production, and the need for efficient management of water resources and soil preservation (Foley et al 2011). Land-use competition between energy production and agriculture has emerged as a critical issue, driving the development of integrated solutions such as agrivoltaic systems.

Semi-transparent photovoltaic panels represent a key innovation within these systems. They are designed to simultaneously capture solar energy and transmit sufficient light for crop photosynthesis, allowing land to serve dual purposes: electricity generation and agricultural production. By adjusting the transparency, height, and spacing of these panels, it is possible to optimize the balance between energy yield and crop productivity, which is particularly important for high-value or light-sensitive crops.

Beyond energy and land-use efficiency, agrivoltaic systems provide several ecological and agronomic benefits. Agrivoltaics create a microclimate that can reduce air temperature and increase water efficiency, potentially providing a promising adaptation solution (Neesham-McTiernan & Barron-Gafford 2025). Additionally, these systems can protect crops from extreme weather events, such as hail, excessive solar radiation, or sudden temperature fluctuations, potentially reducing yield losses and increasing resilience to climate variability.

From an economic standpoint, semi-transparent agrivoltaic systems allow farmers to diversify income sources by selling electricity generated on-site while continuing agricultural production on the same land. Ecologically, these systems contribute to lower greenhouse gas emissions, supporting the transition to sustainable energy while maintaining productive farmland. Agrivoltaics offers a promising alternative to land competition between crops and solar farms, a scalable solution to food, climate, and economic insecurity.

Comparison between traditional and semi-transparent photovoltaic panels. Photovoltaic panels are devices that convert sunlight directly into electricity, providing a renewable and sustainable source of energy. In the context of agriculture, two main types of panels are typically considered: traditional opaque panels and semi-transparent panels (Dupraz et al 2011).

Traditional photovoltaic panels are fully opaque and optimized to capture as much solar radiation as possible. They are widely used in solar farms or on rooftops due to their high energy conversion efficiency. Agrivoltaic system impacts on microclimate and yield of different crops within an organic crop rotation in a temperate climate (Weselek et al 2021). This creates a significant trade-off between land used for energy production and land used for food production, which can limit their suitability for agricultural settings where maximizing crop yield is essential.

Semi-transparent photovoltaic panels, by contrast, are designed to transmit a portion of sunlight while converting the remainder into electricity. Depending on the technology employed - such as thin-film, organic, or perovskite modules - these panels can allow 30-70% of the incoming light to reach crops beneath them. New photovoltaic technologies having higher levels of efficiency have also been developed, such as semi-transparent photovoltaic (STPV) modules, which are based on recently developed dye-synthesized solar cells (DSSCs), and organic photovoltaic cells, which reduce the effect of shading and changes the spectrum of light on traditional opaque PV modules (Gorjian et al 2022). This allows plants to receive sufficient photosynthetically active radiation (PAR), ensuring normal growth and development (Marrou et al 2013). The flexibility in light transmission makes semi-transparent panels ideal for agrivoltaic systems, which aim to combine energy generation with agricultural production on the same land area (Barron-Gafford et al 2019).

From a technical perspective, semi-transparent panels can be implemented in various configurations: i) fixed photovoltaic panels installed about 4 m above crop fields create partial shade conditions that can protect crops from excessive solar radiation while allowing agricultural production underneath (Edouard et al 2023); ii) adjustable or tiltable panels, which can track the sun's movement to optimize both light exposure for crops and energy generation throughout the day (Dinesh & Pearce 2016); iii) panels integrated into greenhouse roofs, allowing controlled light distribution while generating electricity for farm operations (Hassanien et al 2016).

Empirical studies demonstrate several benefits of semi-transparent panels in agriculture: a) microclimate regulation – partial shading reduces soil temperature and prevents overheating of sensitive crops (Barron-Gafford et al 2019); b) Shading from PV panels reduced evapotranspired water by ~14-29%, demonstrating lower soil water loss and therefore reduced irrigation needs (Marrou et al 2013); c) crop protection – panels shield plants from extreme weather events such as hail, strong winds, or sudden temperature spikes; d) energy generation – electricity produced by these panels can power irrigation systems, greenhouse climate control, or on-farm energy needs, providing additional revenue streams (Dupraz et al 2011).

Field trials have shown promising results. For example, vegetables such as lettuce, spinach, and tomatoes grown under semi-transparent panels maintained similar or even higher yields compared to fully exposed crops, while benefiting from improved water-use efficiency and reduced heat stress (Marrou et al 2013). Additionally, integrating semi-transparent panels with bifacial technology, which captures reflected light from the ground, can further enhance energy output without compromising plant growth. Semi-transparent and bifacial PV technologies can be used in agrivoltaics to balance energy production and crop growth (Hickey 2024).

Overall, semi-transparent photovoltaic panels offer a synergistic solution for sustainable agriculture, balancing energy production with crop productivity, improving resource efficiency, and providing resilience to climate variability. Their adaptability to different crops, climatic conditions, and farm layouts makes them a versatile and increasingly viable technology for modern agrivoltaic applications.

Practical examples and case studies of semi-transparent agrivoltaic systems. Semi-transparent photovoltaic panels have been tested in various agricultural contexts worldwide, demonstrating the feasibility and benefits of agrivoltaic systems for simultaneous crop production and energy generation. One common application involves high-value, light-sensitive vegetable crops such as lettuce, spinach, and tomatoes. Studies indicate that these crops can thrive under semi-transparent panels, which provide partial shade, reduce heat stress, and limit soil evaporation. Although lettuce yield was slightly lower in the shaded plots in some cases, the overall yields were comparable and water savings significant, demonstrating that partial shade allowed reductions in water use without substantially compromising crop production (Elamri et al 2018). Partial shading not only improves water-use efficiency but also reduces the risk of thermal damage during hot summer months. Positioning photovoltaic (PV) panels above agricultural areas leads to 2 benefits: it cuts water evaporation from the soil and raises WUE. In arid and semi-arid regions, it is all the more important since water scarcity is a major problem in farming (Ahemd et al 2025). By incorporating semitransparent photovoltaic systems onto greenhouse rooftops, farms can partially generate electricity from solar energy while utilizing the remaining rooftop light transmission to nurture greenhouse plant growth below (Kim et al 2025). For instance, in a controlled greenhouse study, tomato plants grown under semi-transparent perovskite panels received adequate photosynthetically active radiation, while the facility generated enough electricity to cover up to 40% of its energy needs, improving both economic and environmental sustainability.

Agrivoltaic systems can further employ adjustable or tiltable panels, which track the sun or change orientation seasonally to optimize both light distribution for crops and energy production. It was noted that AV systems increased land-use efficiency by up to 70%, underscoring their potential as sustainable solutions in water-scarce regions. Additionally, AV systems contribute to climate adaptation by providing shade, which mitigates heat stress and supports water conservation (Omer et al 2025). These flexible installations allow for crop-specific adaptations: taller crops or perennials can receive more sunlight, while smaller, shade-tolerant crops benefit from moderate shading and microclimate stabilization.

Across multiple case studies, the benefits of semi-transparent agrivoltaic systems are clear. In addition to renewable energy, we find that AVS provide co-benefits such as enhanced crop/pasture water-use efficiencies (up to 150-300% improvement), greater land-use efficiency (up to 200%), reduced irrigation demand (14% reduction), improved profitability (up to 15 times higher revenue) and more consistent interannual crop/pasture production compared with conventional agricultural production systems in isolation. Such synergies amplify in locations characterized by arid, semi-arid and hot conditions that are conducive to transient or chronic plant water deficit (Pandey et al 2025). These examples demonstrate that semi-transparent photovoltaic panels are not merely a theoretical concept but a practical solution for modern agriculture, capable of enhancing sustainability, resilience, and profitability simultaneously (Barron-Gafford et al 2019).

Challenges and future perspectives. Despite the clear advantages of semi-transparent agrivoltaic systems, several challenges must be addressed to enable widespread adoption and long-term sustainability. These challenges are both technical and socio-economic, and addressing them will determine the success of this innovative technology in the agricultural sector (Dupraz et al 2011; Barron-Gafford et al 2019). One of the primary obstacles is the high upfront cost associated with installing semi-transparent photovoltaic panels, which includes not only the panels themselves but also specialized support structures, inverters, wiring, and monitoring systems. Potential solutions include government subsidies or low-interest loans for agrivoltaic installations, public-private partnerships to spread investment risk, and cooperative models in which farmers share infrastructure and benefits.

Agrivoltaics is still an emerging field, and in many countries, there is no clear regulatory framework for dual-use land systems. Challenges include unclear grid connection regulations for electricity generated on farmland, a lack of incentives for combining energy and food production compared to standard renewable energy projects, and potential conflicts with land zoning laws or agricultural subsidies that do not account for partial land-use modification. To overcome these challenges, policymakers need to develop specific regulations and incentive schemes that recognize the multifunctionality of agrivoltaics, encouraging adoption without penalizing farmers.

Optimizing semi-transparent agrivoltaic systems requires careful attention to both energy production and agronomic outcomes. Panel height and spacing need to accommodate crop growth, machinery, and irrigation equipment, while orientation and tilt must be adapted seasonally to maximize solar capture without reducing crop yields. Crop selection is crucial, as not all plants respond equally to partial shading; leafy vegetables, berries, and shade-tolerant cereals tend to perform better under semi-transparent panels (Marrou et al 2013).

While agrivoltaics can mitigate some climate-related challenges, there are environmental factors that must be carefully managed. Panel installation may alter local microclimates in ways that affect soil moisture, temperature, and pest dynamics. Heavy panel structures can impact soil compaction, requiring careful ground management and support design. The long-term effects on biodiversity and soil ecosystems are still being studied, particularly in regions where agrivoltaics replace natural habitats (Barron-Gafford et al 2019).

Ongoing research aims to improve efficiency, reduce costs, and enhance the multifunctionality of semi-transparent agrivoltaic systems. Advances include the development of highly transparent, durable organic and perovskite PV modules with tunable light transmission, smart systems that automatically adjust orientation, tilt, or opacity based on solar position, crop stage, and environmental conditions, integration with precision agriculture using sensors, artificial intelligence, and automated irrigation to optimize crop growth and energy yield, scalable modular systems suitable for small farms, large commercial operations, and greenhouse integration, and socio-economic studies evaluating long-term adoption, farmer behavior, and economic viability in different cultural and climatic contexts (Dinesh & Pearce 2016).

As climate change intensifies and land scarcity increases globally, semi-transparent agrivoltaic systems are likely to become essential tools for sustainable land management. They provide a multifunctional approach by generating renewable energy, increasing crop resilience to heat, drought, and extreme weather, improving water-use efficiency, and supporting economic diversification for farmers. With continued technological innovation, supportive policies, and farmer engagement, semi-transparent agrivoltaics could play a central role in climate-resilient agriculture, ensuring both food security and energy sustainability in the 21st century (Dupraz et al 2011).

Conclusions. The integration of semi-transparent photovoltaic panels into agricultural systems represents a significant advancement in sustainable land use, offering a multifunctional solution to the growing global challenges of energy production and food security. Unlike traditional opaque solar panels, which prioritize electricity generation at the expense of agricultural productivity, semi-transparent panels allow simultaneous crop cultivation and energy harvesting, optimizing land use and maximizing resource efficiency.

These systems improve the microclimate for crops by providing partial shading, reducing soil evaporation, and protecting plants from heat stress, hail, or excessive solar radiation. As a result, they contribute not only to enhanced crop resilience and water-use efficiency but also to climate adaptation strategies, making agriculture more resilient to extreme weather events and shifting environmental conditions.

From an economic perspective, semi-transparent agrivoltaic systems create dual revenue streams, offering income from both agricultural production and electricity generation. This reduces financial risk for farmers and supports the development of more sustainable and diversified rural economies. Environmentally, these systems reduce greenhouse gas emissions by producing clean energy, while simultaneously promoting more efficient and sustainable use of agricultural land.

While challenges remain, including higher initial investment, technical design complexities, and gaps in regulatory frameworks, ongoing technological advancements - such as smart tilting panels, adjustable transparency, and integration with precision agriculture - are expected to enhance their performance and accessibility. With these innovations, semi-transparent agrivoltaic systems have the potential to play a critical role in future agricultural landscapes, supporting both food security and renewable energy goals in a climate-resilient and environmentally responsible manner.

In conclusion, semi-transparent photovoltaic panels offer a holistic and forward-looking approach to modern agriculture, effectively bridging the gap between energy sustainability and crop productivity, and positioning agrivoltaics as a key solution for the challenges of the 21st century.

Conflict of interest. The author declares that there is no conflict of interest.

References

Ahemd R., Izaz M. H. B., Manik K. H., Khatun H., Nath A., Mim J. J., Hossain N., 2025 Advancements in agrivoltaic systems for enhanced sustainable energy utilization - a review. Environmental Challenges 20:101299.

Barron-Gafford G. A., Pavao-Zuckerman M. A., Minor R. L., Sutter L. F., Barnett-Moreno I., Blackett D. T., Thompson M., Dimond K., Gerlak A. K., Nabhan G. P., Macknick J. E., 2019 Agrivoltaics provide mutual benefits across the food-energy-water nexus in drylands. Nature Sustainability 2(9):848-855.

Dinesh H., Pearce J. M., 2016 The potential of agrivoltaic systems. Renewable and Sustainable Energy Reviews 54:299-308.

Dupraz C., Marrou H., Talbot G., Dufour L., Nogier A., Ferard Y., 2011 Combining solar photovoltaic panels and food crops for optimising land use: towards new agrivoltaic schemes. Renewable Energy 36(10):2725-2732.

Edouard S., Combes D., Van Iseghem M., Tin M. N. W., Escobar-Gutiérrez A. J., 2023 Increasing land productivity with agriphotovoltaics: application to an alfalfa field. Applied Energy 329:120207.

Elamri Y., Cheviron B., Lopez J. M., Dejean C., Belaud G., 2018 Water budget and crop modelling for agrivoltaic systems: application to irrigated lettuces. Agricultural Water Management 208:440-453.

Foley J. A., Ramankutty N., Brauman K. A., Cassidy E. S., Gerber J. S., Johnston M., et al, 2011 Solutions for a cultivated planet. Nature 478(7369):337-342.

Gorjian S., Bousi E., Özdemir Ö. E., Trommsdorff M., Kumar N. M., Anand A., Kant K., Chopra S. S., 2022 Progress and challenges of crop production and electricity generation in agrivoltaic systems using semi-transparent photovoltaic technology. Renewable and Sustainable Energy Reviews 158:112126.

Hassanien R. H. E., Li M., Lin W. D., 2016 Advanced applications of solar energy in agricultural greenhouses. Renewable and Sustainable Energy Reviews 54:989-1001.

Hickey T., Uchanski M., Bousselot J., 2024 Vegetable crop growth under photovoltaic (PV) modules of varying transparencies. Heliyon 10(16):e36058.

Kim S. Y., Rayes N., Kemanian A. R., Gomez E. D., Doumon N. Y., 2025 Semitransparent organic and perovskite photovoltaics for agrivoltaic applications. Energy Advances 4(1):37-54.

Marrou H., Dufour L., Wery J., 2013 How does a shelter of solar panels influence water flows in a soil-crop system? European Journal of Agronomy 50:38-51.

Neesham-McTiernan T. H., Barron-Gafford G. A., 2025 The long-term suitability of agrivoltaics as a climate adaptation strategy in the southwestern United States. Global Environmental Change Advances 5:100021.

Omer A. A. A., Li M., Zhang F., Hassaan M. M. E., El Kolaly W., Zhang X., Lan H., Liu J., Liu W., 2025 Impacts of agrivoltaic systems on microclimate, water use efficiency, and crop yield: a systematic review. Renewable and Sustainable Energy Reviews 221: 115930.

Pandey G., Lyden S., Franklin E., Millar B., Harrison M. T., 2025 A systematic review of agrivoltaics: productivity, profitability, and environmental co-benefits. Sustainable Production and Consumption 56:13-36.

Weselek A., Bauerle A., Hartung J., Zikeli S., Lewandowski I., Högy P., 2021 Agrivoltaic system impacts on microclimate and yield of different crops within an organic crop rotation in a temperate climate. Agronomy for Sustainable Development 41(5):59.

Received: 18 October 2025. Accepted: 30 November 2025. Published online: 24 December 2025.

Authors:
Alexandra Maria Chețan, Department of Environmental Engineering and Protection, Faculty of Agriculture, University of Agricultural Sciences and Veterinary Medicine of Cluj-Napoca, 3-5 Calea Mănăştur Street, 400372 Cluj-Napoca, Romania, e-mail: alexandra-maria.chetan@student.usamvcluj.ro
Alexandra Ioana Ciolpan, Department of Environmental Engineering and Protection, Faculty of Agriculture, University of Agricultural Sciences and Veterinary Medicine of Cluj-Napoca, 3-5 Calea Mănăştur Street, 400372 Cluj-Napoca, Romania, e-mail: alexandra-ioana.ciolpan@student.usamvcluj.ro
Robert Andrei Kudor, Department of Environmental Engineering and Protection, Faculty of Agriculture, University of Agricultural Sciences and Veterinary Medicine of Cluj-Napoca, 3-5 Calea Mănăştur Street, 400372 Cluj-Napoca, Romania, e-mail: robert-andrei.kudor@student.usamvcluj.ro

How to cite this article:
Chețan A. M., Ciolpan A. I., Kudor R. A., 2025 Transparent and semi-transparent photovoltaic panels in agrivoltaic systems: enhancing sustainable agriculture and renewable energy production. AAB Bioflux 17(1):69-74.