

Harvesting the Sun Twice: A Multidisciplinary Review of the Agrivoltaic Frontier

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Only about 29% of the Earth's landmass is considered habitable, with about 44% of that habitable land being devoted to agriculture. Cropland consumes about one third of agricultural land, and grazing land compromises the rest. Additionally, 84% of this agricultural cropland is used to grow food for livestock, biofuels, and other industrial products, which leaves only 16% of cropland used for direct human consumption (Ritchie, 2024). With this, there has also been a growing demand for more energy, and global energy demand is expected to increase 70% by 2050 (Exxon, 2025). As the population continues to grow, and as agricultural lands continue to face new challenges and strains, there is a necessity to meet both the global energy demand and global food supply demand. Photovoltaic (PV) systems are increasingly occupying agricultural lands in the US, driven by a high demand for renewable energy and attractive federal and state incentives for landowners (Institute for Energy Research, 2024). This trend has raised concerns about the loss of food production and farmland fragmentation, but it has simultaneously spurred the growth of agrivoltaic (AV) systems. AV comes in many different forms, from coexistence of crops and PV systems on the same land to a complete combination of the two (Sollazzo et al., 2025). The field of AV production has evolved into a sophisticated domain of engineering and microclimate manipulation. While there is current research being done to determine if AV systems are truly as "win-win" as they seem, global adoption is hindered by technical, biological, and socio-economic hurdles. This review will synthesize current literature across four critical dimensions: hardware evolution, crop physiology, socio-economic frameworks, and specialized niche applications. This paper will aim to identify key research gaps and help provide a roadmap for the next generation of integrated crop food-energy systems.

The Engineering Frontier

AV systems offer a resource-efficient renewable energy system, especially in regions that are particularly dense or have limited agricultural land area. Crop areas that suffer from high solar radiation and high water loss that have implemented AV systems have seen up to a 30% increase in income (Chopdar, 2024). These panels can make the ground more productive, more valuable, improve crop yields, improve water efficiency, lower ambient temperatures, diversify income, all while saving land resources and boosting land use efficiency by 70% (Dupraz et al., 2011). Recent AV product design and technology has included researching panel heights, PV panel types, solar trackers, and various other innovations.

The height and interspacing of AV modules is critical to optimize performance of both the panels and the crops below. A study done by Tromssdorf et al. (2021) found that AV productivity is best around four meters in height and another study done by Abidin et al. found that AV productivity peaks when modules are around 1.21 to 1.52 meters apart. While research continues to be done to optimize AV configurations for each crop, the optimal configurations of height and interspacing depend on crop requirements, panel design, available sunlight, and regional climate.

In terms of AV array development, the Montpellier Experimental Agrivoltaic Station has designed, built, and tested different types of AV systems to find that full density structures maximize solar power generation, but half density structures optimize both electricity and agricultural output. The UMass Crop Research Farm came to a similar conclusion, both recording that if 70% of solar energy reaches the crops below then agricultural and electrical output will be optimized. The majority of the studies have noted that optimal AV array development depends on crop type and geographic location.

The two main types of AV are fixed type, which are stationary and take up more space on land, and dynamic type, which move to follow the sun's positioning. Fixed type AVs are ground mounted, stilt-mounted, greenhouse and rooftop AVs. Dynamic type AVs include a variety of other configurations. The most studied configuration of AV is the overhead/roof-mounted version, because it maximizes solar exposure while also including the shielding effect of PV panels. There have been multiple studies highlighting the effectiveness of different panel materials, especially regarding the traditional silicon PV (Si PV) panels and semi-transparent organic (STO) panels. Si PV panels are completely opaque, blocking most sunlight directly underneath while also providing significant shade and reducing heat stress to those crops. STO panels are partially transparent and allow some light to pass through (Sollazzo, 2025). Apriani et al. (2024) conducted a study on the effectiveness of bok choy cultivation with overhead Si PV panels, STO panels, and no cover (as a control). The plants grown under STO had a mean crop yield 1.4-1.8% greater than those of the plants grown under no cover and under the Si PV panels. Similarly, Blando et al. (2018) conducted a study characterizing the growth of raspberries, strawberries, and blackberries inside three commercial greenhouses (STO, Si PV, and transparent polycarbonate). The effects of the different conditions were evaluated in terms of the levels of anthocyanin, the bioactive compound, in the various cultivars. Anthocyanin, glucose, and fructose content was highest in STO panels for both the raspberries and strawberries and it was lowest in the transparent polycarbonate. Blackberries had highest levels under Si PV panels and lowest under the STO panels. Tang et al. (2020) conducted a very similar study and found that strawberry plants cultivated under Si PV shading had a 17% higher yield and 10% higher fruit mass and size compared to unshaded plants. This research being done allows for AV

technologies to increase and enhance panel productivity based on crop type, which will lead to both an increase in crop yield and energy yield.

Outside of this, there are further engineering advancements being made in the field of AV: solar trackers, concentrated-lighting agrivoltaic systems, organic photovoltaics, semi-transparent PV panels, smart sensors, bifacial modules, spectral-selective filters, structural innovations, intentional crop selections, and various digitization practices to increase the land-use efficiency (Chopdar et al., 2024). While these engineering advancements provide the physical framework, the ultimate viability of these systems is dictated by the biological limits of the vegetation underneath. As PV materials shift toward spectral selectivity, the focus moves from simply providing shade to actively tailoring the light environment to meet specific photosynthetic requirements.

The Biological and Microclimate Impact

Managing the Water-Energy-Food Nexus (WEF) is becoming increasingly crucial, as all three of the pillars are critical for everyday functioning (Messaoudi, 2024). The WEF refers to the interconnectivity of water, energy, and food systems, as changes in one can directly impact the other. AV systems can foster synergy between these sectors. The shade these AV systems produce reduces soil temperature, which helps maintain moisture levels and sustain microbial life. This reduces direct evaporation from the ground, heat stress, and transpiration levels (Maity et al., 2025). A study done at the University of Arizona found that shading from panels improves water-use efficiency, with their jalapenos in the covered and AV plot producing a similar amount of fruit, but the jalapenos in the AV plot experiencing 65% less transpirational water loss with 15% higher soil moisture content (Barron-Gafford, 2019). While producing food, the panels also produce sustainable energy that can power irrigation, local communities, or be fed back into the

grid. In regions facing high heat and water loss, AV systems can help maintain the WEF and help balance all three pillars for a functioning human society. The physiological benefits provide a strong scientific case for agrivoltaics; however, translating these field-level successes into regional adoption requires a supportive regulatory and economic landscape.

Research is being completed to determine growth responses of certain crops under AV conditions. Data analysis under Laub et al. (2022) used 58 studies on the effects of shade in 38 different crop species for a total of 428 data points to determine how much shade these crops can handle while optimizing agricultural and energetic production. They found that at around 50% shade, all crops show poorer susceptibility to shade responses. Berries, fruits, and fruiting vegetables benefitted from up to 30% shade. Forages, leafy vegetables, tubers, and root crops also were found to be relatively shade tolerant and did not lose as much yield. Studies like these help provide information and indicators to assess the suitability of different crops under agrivoltaic conditions. Additionally, a study done by Pascaris et al. (2021) researched integrated agrivoltaic systems (specifically in pasture-based systems) and established that they can reduce greenhouse gas emissions by 69.3% and lower fossil energy demand by 82.9% compared to traditional, independent, "non-integrated" agricultural practices.

Outside of crop and energy production, research has found that agrivoltaics can help produce a “win-win” situation for agricultural areas where transpiration from the crops below cool panels up to 10 degrees celsius, which in turn boosts panel productivity by 2-5% per panel (Tauz-Posch, 2022). Solar panels lose efficiency as they heat up, and it has been found that the moisture released through crop transpiration acts as a natural air conditioner, creating a cooler microclimate underneath the arrays to improve energy yields. The shade provided by the panels protects plants from extreme heat and high evaporation rates, reducing water irrigation

requirements. In addition to crops, livestock can graze under panels, providing them with shade and reducing heat stress. This system has been found particularly effective in dryland areas, where resources can be maximized to create a symbiotic relationship between the two (Maity et al., 2025). Despite the clear biological synergies between panels and crops, the 'Triple Bottom Line' (economic, social, and environmental) remains the primary hurdle for large-scale commercial investment.

Socio-Economic Barriers

The transition from technical feasibility to widespread commercial adoption is primarily governed by a complex interplay between economic viability and regional policy. In terms of economic viability and profitability, agrivoltaics provide a dual income stream for many farmers through electricity sales and agriculture. Research has found that certain agrivoltaic systems could be up to 270% more profitable than standalone cropping systems (Jean, 2025). A study done in India found that their agrivoltaics system indicated a 240% land equivalent ratio increase, showing almost double the land use efficiency. In their economic analysis, they found that while initial investments are high, the payback will surpass that of traditional mono-cropping (Trommsdorf et al., 2021). Due to the high initial capital expenditures, there is a significant barrier to adoption, and success is often linked to government subsidies or a high local demand for energy. Additionally, a 2021 survey of two communities in Texas and Michigan found that 81.8% of respondents were more likely to support solar development if it integrated agricultural production (Pascaris et al., 2023).

The global landscape of agrivoltaics is further shaped by how individual nations define and regulate the technology. France's rigorous legal definition prioritizes agricultural primacy and productivity, acting as a national framework that drives structured adoption, while US,

state-level, zoning-based policies offer more flexibility but create a fragmented, project-by-project adoption landscape. France ensures panels enhance agricultural sustainability, whereas the U.S. approach focuses on land-use regulations. France and other countries in the EU define agrivoltaics strictly, ensuring it is a tool to protect agricultural production rather than replace it. The definition ensures that agricultural activity is the main purpose, and the PV system is secondary (Trommsdorf et al., 2024). In the U.S., agrivoltaic policies are largely fragmented, driven by local zoning laws and state-level incentives, rather than a national definition. Policies vary significantly by states, leading to faster, but sometimes inconsistent, development. The lack of a national standard can lead to land-use conflicts and uncertainty regarding whether projects are truly dual-use (Pascaris et al., 2022). France's approach ensures high-quality, purposeful installations, while U.S. zoning allows for rapid experimentation and faster deployment in some areas. France's legal framework is better at protecting agricultural land from displacement, whereas U.S. adoption is often driven by land-use efficiency and economic benefits. As the science matures, the tension between protectionist legal definitions and market-driven flexibility will likely dictate the speed and quality of global adoption.

Specialized Multi-Use Applications and Ecosystem Services

Beyond the economic and regulatory hurdles, the synergy of solar and agriculture offers transformative advantages for livestock management and ecological health. Solar grazing with sheep is widely considered the most effective livestock-based vegetation management method, while pollinator-friendly solar sites improve biodiversity and reduce long-term maintenance costs. Solar panels provide essential shade, reducing the radiant heat load on livestock by up to 30%. Studies show that shade from panels can cool a cow's body surface by 10.8 degrees Fahrenheit and reduce wool-surface temperatures on sheep by 7 to 8 degrees Celsius, creating a

more comfortable, less stressful environment (Fonseca et al., 2023). Panels also protect animals from wind and rain. Vegetation under solar panels can have higher protein content and improved digestibility compared to open pasture. The panels prevent soil from parching and "drip-feed" the grass with dew, enhancing growth and quality, particularly in hot, arid conditions (Kampherbeek et al., 2023). Solar grazing can reduce vegetation management costs by up to 30% or more compared to mechanical mowing, as it eliminates the need for expensive fuel, labor, and herbicide use (American Solar Grazing Association, 2020).

The ecological benefits of agrivoltaics extend to the restoration of local biodiversity through pollinator-friendly solar sites. Planting native wildflowers and grasses instead of turfgrass creates vital habitats for pollinators, such as bees and butterflies. Studies found that insect abundance tripled at these sites in under 5 years, with native bee numbers increasing by 20-fold (Huber, 2024). Deep-rooted native plants improve soil health, increase carbon sequestration, and reduce erosion and runoff. The vegetation also mitigates the "heat island" effect around panels, which can improve their energy efficiency (Dute, 2023). Additionally, "Solar Grown" honey is a growing industry and hives placed at solar sites benefit from diverse pollen sources, which can improve their immune response to pathogens (Dolezal et al., 2021). While initial installation can be higher, maintaining native, pollinator-friendly vegetation is 80%–90% less expensive than turf over ten years, requiring only annual mowing and no fertilizers or pesticides (Janke, 2021).

Synthesis and Future Directions

The current body of literature demonstrates that agrivoltaics has moved beyond a niche experimental concept into a sophisticated, multidisciplinary solution for the global land-use conflict. By integrating hardware evolution, crop physiology, and socio-economic frameworks,

AV systems provide a viable pathway to meet the projected 70% increase in global energy demand by 2050 (Exxon, 2025) while simultaneously protecting the finite 29% of Earth's habitable landmass (Ritchie, 2024). The "win-win" nature of these systems is characterized by significant gains in land-use efficiency, up to 70% in some models (Dupraz et al., 2011), and the potential for profitability increases of up to 270% compared to standalone cropping (Jean, 2025). However, for the next generation of integrated food-energy systems to reach maturity, several critical research gaps must be addressed.

First, while research has identified that optimal productivity often occurs at panel heights of approximately four meters with interspacing of 1.21 to 1.52 meters, these configurations remain highly sensitive to regional climates and specific crop requirements. Future studies must pivot from general optimization to specialized designs for staple cereal crops. Additionally, as technology shifts toward semi-transparent organic (STO) panels and spectral-selective filters, there is a need for long-term physiological studies to determine if the 1.4-1.8% yield increases seen in pilot studies are sustainable over multiple growing seasons (Aprini et al., 2024).

Furthermore, the "vapor-shield" effect and the cooling of panels by crop transpiration (by up to 10 degrees Celsius) offer a compelling case for AV deployment in arid regions (Tauf-Pesch, 2022). Yet, the transition from these biological successes to regional adoption is currently hindered by fragmented policy landscapes. The contrast between France's centralized "agricultural primacy" framework and the United States' decentralized, state-level zoning suggests that a major future research direction must involve the standardization of legal definitions for dual-use projects. Without national standards, land-use conflicts and "greenwashing" may impede social acceptance, despite some levels of community support for integrated systems.

Finally, the expansion of AV into specialized applications, such as solar grazing and pollinator habitats, indicates a move toward "Ecosystem Services" as a primary value driver. The ability of native wildflowers to increase bee populations 20-fold (Huber, 2024) while reducing long-term maintenance costs by 80-90% represents a significant operational breakthrough (Janke, 2021). Future research should focus on quantifying these "soft" economic benefits, such as carbon sequestration and improved immune responses in pollinators, to create a more holistic "Triple Bottom Line" analysis for prospective investors. Bridging these technical and regulatory gaps will be essential to transforming agrivoltaics from a series of successful pilot programs into a global standard for sustainable resource management.

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