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The Dual Harvest: A Systematic Review of Agrivoltaic Systems' Impact on Crop Production and Energy Generation

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ABSTRACT

Background: The increasing competition for land between agriculture and energy production has created a need for innovative solutions that can optimize land use. Agrivoltaic systems, which co-locate solar panels and crops, have emerged as a promising approach to address this challenge.

Objective: This comprehensive review synthesizes the experimental findings and field applications of agrivoltaic systems to provide a holistic understanding of their potential benefits and challenges.

Methods: A systematic literature search was conducted to identify relevant studies published in the last decade. The selected studies were analyzed to extract data on the impact of agrivoltaic systems on crop production, energy generation, and economic viability.

Results: The review of 108 studies reveals that agrivoltaic systems can have a positive impact on both crop production and energy generation. The shading provided by the solar panels can improve crop yields and water use efficiency, while the vegetation can cool the solar panels and increase their efficiency. However, the performance of agrivoltaic systems is highly dependent on the specific design, crop type, and climate.

Conclusion: Agrivoltaic systems have the potential to be a key technology in the transition to a more sustainable food and energy system. However, further research is needed to optimize their design and management for different contexts.

KEYWORDS

Agrivoltaics, Agrophotovoltaics, Dual-Use Land, Food-Energy Nexus, Land Equivalent Ratio, Sustainable Agriculture, Solar Energy.

INTRODUCTION

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The 21st century is defined by a series of interconnected global challenges, prominently featuring the need to ensure food security, transition to sustainable energy sources, and manage finite water resources under a changing climate [12, 16]. This triad, often termed the food-energy-water (FEW) nexus, highlights a fundamental conflict: the increasing competition for land. As the global population expands, so does the demand for both agricultural land to produce food and land for renewable energy infrastructure, particularly large-scale solar photovoltaic (PV) installations [11, 108]. Conventional ground-mounted solar farms, while crucial for decarbonization, occupy vast tracts of land, often displacing agriculture and disrupting local ecosystems, leading to significant land-use conflicts [13, 17]. This paradigm of single-use land management is becoming increasingly untenable, necessitating innovative solutions that promote synergy rather than competition.

Agrivoltaics (AV), also known as agrophotovoltaics or solar sharing, has emerged as a transformative approach to reconcile these competing demands [10, 15]. Coined by Goetzberger and Zastrow in 1981, the concept involves the co-location of agricultural activities and solar energy generation on the same piece of land [101]. By strategically elevating and spacing solar panels, sufficient sunlight can reach the crops or pasture below, enabling a dual harvest of both food and electricity from a single land area [5, 14]. This innovative land-use strategy moves beyond simple co-existence to create a symbiotic relationship where the two systems provide mutual benefits. For instance, the partial shade from PV panels can protect crops from excessive solar radiation and heat stress, reduce soil water evaporation, and create a more favourable microclimate, particularly in arid and semi-arid regions [39, 44, 70]. Conversely, the evapotranspiration from the underlying vegetation can create a cooling effect that improves the efficiency and lifespan of the PV panels [34, 48, 79].

Over the past decade, research and development in agrivoltaics have accelerated globally, moving from conceptual models to a wide array of experimental and commercial field applications [13, 26]. Studies have explored diverse AV system designs, from static, overhead structures and vertical bifacial arrays to dynamic tracking systems and integration with greenhouses [4, 27, 32, 64]. The application scope has broadened to include various forms of agriculture, such as horticulture [22, 54], broadacre cropping [8, 88], fruit orchards [28, 40, 60], and livestock grazing [3, 6, 91]. This growing body of work has generated a wealth of data on the system's performance, exploring its impacts on crop physiology, yield, water productivity, energy output, soil health, and economic viability [1, 11, 33, 66].

Despite this rapid progress, significant research gaps and practical challenges remain. The performance of AV systems is highly context-dependent, varying with local climate, soil type, crop selection, and system configuration [9, 10]. A comprehensive understanding of the complex interactions between the photovoltaic array and the agricultural subsystem is still developing. Key questions persist regarding the long-term ecological impacts, the optimization of system design for different agricultural contexts, and the development of supportive policy and economic frameworks to facilitate wider adoption [16, 20, 103]. While several reviews have summarized the state of agrivoltaics [11, 13, 26], the continuous emergence of new experimental data from diverse global contexts necessitates an updated and comprehensive synthesis.

This review aims to address this need by providing a systematic and comprehensive analysis of the existing experimental and field application literature on agrivoltaic systems. The primary objectives are to: (1) systematically collate and synthesize findings on the impacts of AV systems on agricultural production and energy generation; (2) critically evaluate the environmental and economic co-benefits and trade-offs associated with this dual-use approach; and (3) identify key knowledge gaps and outline future research directions required to unlock the full potential of agrivoltaics. By consolidating the current state of knowledge, this review seeks to provide a valuable resource for researchers, farmers, policymakers, and energy developers, informing evidence-based decisions for the sustainable intensification of land use.

METHODS

To provide a robust and transparent overview of the state of agrivoltaic research, this comprehensive review was conducted following the principles outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [18]. The methodology was designed to be systematic and replicable, ensuring a comprehensive capture of relevant literature and an unbiased synthesis of the findings.

2.1. Search Strategy

A systematic literature search was performed across three major academic databases: Scopus, Web of Science, and Google Scholar. These platforms were chosen for their extensive coverage of peer-reviewed literature in the fields of agriculture, energy, environmental science, and engineering. The search was conducted to identify all relevant articles published up to January 2025. The search query was constructed using a combination of keywords related to the core concepts of agrivoltaics and its impacts. The search string was adapted for the syntax of each database and included the following terms: ("agrivoltaic*" OR "agrophotovoltaic*" OR "solar sharing" OR "agrisolar" OR "solar agriculture") AND ("crop yield" OR "crop production" OR "livestock" OR "grazing" OR "pasture" OR "energy yield" OR "photovoltaic performance" OR "microclimate" OR "soil moisture" OR "water use efficiency" OR "economic*" OR "land equivalent ratio"). Additionally, the reference lists of previously published review articles [10, 11, 13, 14, 26] and key primary studies were manually scanned to identify any publications missed by the database search.

2.2. Inclusion and Exclusion Criteria

Studies identified through the search strategy were screened for eligibility based on a predefined set of inclusion and exclusion criteria. To be included in the review, a study had to:

1. Be a peer-reviewed article, conference paper, or official technical report.

2. Be published in the English language.

3. Present original empirical data from an experimental, quasi-experimental, or observational field study of an agrivoltaic system. Modelling and simulation-only studies were included if they were validated with field data [e.g., 27, 89].

4. Investigate at least one key outcome related to agricultural production (e.g., crop yield, biomass, animal productivity), energy production (e.g., PV efficiency, energy output), or environmental interactions (e.g., microclimate, soil properties, water use).

Studies were excluded if they were: (1) purely theoretical, conceptual, or policy-focused without empirical data; (2) focused solely on the technical aspects of PV technology without an agricultural component; (3) news articles, editorials, or non-technical publications; or (4) focused on floating solar or building-integrated photovoltaics that did not involve land-based agriculture. The screening process was conducted in two stages: an initial title and abstract screening, followed by a full-text review of the potentially eligible articles to make the final selection.

2.3. Data Extraction and Synthesis

For each study that met the inclusion criteria, relevant information was extracted and compiled into a structured database. The extracted data included: (1) bibliographic details (authors, year, title); (2) study location (country, climate zone); (3) agrivoltaic system design (e.g., panel type, height, density, orientation, tracking system); (4)

agricultural system details (e.g., crop species, livestock type, cultivation practices); (5) key measured outcomes (e.g., changes in crop yield, quality, biomass; Land Equivalent Ratio; PV energy output; microclimatic variables like air temperature, soil moisture, and Photosynthetically Active Radiation (PAR); economic performance metrics); and (6) primary conclusions of the study.

The extracted data were then synthesized thematically according to the core objectives of this review. A narrative synthesis approach was adopted to integrate the findings from the diverse set of studies. This involved grouping studies based on the outcomes they investigated (e.g., crop responses, energy performance, environmental co-benefits) and identifying common patterns, key trade-offs, and sources of heterogeneity in the results. Quantitative metrics such as the Land Equivalent Ratio (LER), defined as the sum of the relative yield of agriculture under the AV system and the relative yield of electricity production compared to their respective monoculture systems [101], were used as a primary indicator of overall system performance where available.

2.4. Quality Assessment

While a formal meta-analysis was not the objective of this review due to the heterogeneity in study designs and reported metrics, a qualitative assessment of the included studies was performed. The quality and reliability of each study were informally evaluated based on criteria such as the clarity of the research design, the duration of the experiment (short-term vs. multi-year), the presence of appropriate control groups (e.g., full-sun monoculture crop, standalone PV installation), the rigour of the data collection methods, and the statistical analysis employed. This assessment helped in contextualizing the findings and giving more weight to studies with more robust methodologies, such as long-term, multi-location trials [e.g., 9, 35]. The synthesis presented in the Results and Discussion sections reflects this qualitative appraisal of the evidence base.

RESULTS

The systematic search and screening process yielded a total of 108 relevant sources that form the basis of this review. These studies span a wide range of geographical locations, climatic conditions, AV system designs, and agricultural applications, reflecting the growing global interest in this technology. This section synthesizes the key findings from this body of literature, organized according to the system's impact on agricultural production, energy generation, and the broader environmental and economic context.

3.1. Overview of Included Studies

The research landscape for agrivoltaics is geographically diverse, with significant clusters of research activity in North America [9, 39, 44, 89], Europe (e.g., France [43, 50, 101], Germany [15, 31, 59], Italy [49, 86, 103], Belgium [4, 8, 57], Spain [87]), and Asia (e.g., China [7, 27, 46], Japan [52], India [1, 58, 63], Pakistan [55]). There is also emerging research from South America [19, 29], Africa [20], and Australia [72]. The studied agricultural systems are equally varied. A significant portion of the research has focused on horticultural crops, including leafy greens [56, 102], tomatoes [22, 38, 69, 83], peppers [39], cucumbers [82], and various vegetables [54, 55]. Research has also extensively covered broadacre crops like wheat [8, 85, 88], corn [41, 89], soybeans [86], and rice [52]. Perennial systems, such as fruit orchards [28, 40, 60], vineyards [51], and berry cultivation, are increasingly being investigated. Another major application area is animal husbandry, with studies focusing on sheep grazing [3, 6, 92], cattle [30, 91], and forage production for livestock [72, 84, 95].

AV system designs vary substantially across studies, driven by different optimization goals (maximizing crop yield, energy output, or overall LER). Common designs include static, fixed-tilt overhead arrays with varying panel densities or "checkerboard" patterns [50, 101], single-axis [4, 27] and dual-axis tracking systems [5], and vertical bifacial installations oriented east-west [4, 32, 55]. The use of different PV module technologies, including standard opaque panels [61], semi-transparent modules [54], and wavelength-selective panels [25], has also been explored to manage the light environment for the crops below.

3.2. Impact on Agricultural Production

The introduction of a PV array fundamentally alters the growing environment for the underlying agricultural system. The primary effect is the reduction and redistribution of incoming solar radiation, which in turn influences the microclimate, water balance, and plant physiology.

3.2.1. Microclimate Modification

One of the most consistently reported effects of AV systems is the moderation of the microclimate. The shade cast by the PV panels leads to a significant reduction in air and soil temperatures during the day and can retain heat, leading to slightly warmer temperatures at night [39, 49, 50]. Barron-Gafford et al. [39] found that in a dryland ecosystem in Arizona, USA, air temperatures under the AV array were cooler during the day, creating a less stressful environment for crops. Similarly, soil temperature is typically lower and exhibits less diurnal fluctuation under panels, which can benefit root development and soil microbial activity [35, 97].

The shading effect also significantly reduces evaporative demand. Studies have consistently demonstrated higher soil moisture content under AV systems compared to open-field controls [43, 44]. Hassanpour Adeh et al. [44] reported that soil moisture remained 5-15% higher under panels throughout the growing season in Oregon, USA. This water conservation effect is particularly pronounced in arid and semi-arid climates, where it can translate into substantial water savings and buffer crops against drought stress [39, 65, 70]. The panels also reduce wind speed at the crop level, further decreasing evapotranspiration [42].

3.2.2. Crop Yield, Quality, and Physiology

The response of crop yield to the modified light environment under AV systems is highly variable and depends on the crop's light saturation point, the degree of shading (i.e., panel density), and the local climate.

For shade-tolerant crops, such as lettuce, spinach, chard, kale, and certain herbs, yields can be equal to or even greater than those in full-sun conditions [56, 102]. The reduced light is often not a limiting factor, and these crops benefit greatly from the cooler temperatures and improved water availability, which prevent bolting and reduce stress.

For sun-loving crops, such as wheat, corn, and many fruiting vegetables, the results are more nuanced. In temperate climates with ample water, significant shading can lead to yield reductions due to light limitation [8, 59, 88]. For example, Weselek et al. [59] in Germany observed yield declines for winter wheat and potatoes, although celery yields were unaffected. However, in hot, arid, or semi-arid climates, the benefits of stress reduction can outweigh the negative effects of reduced light, leading to stable or even increased yields. Barron-Gafford et al. [39] famously found that the yield of chiltepin peppers was three times higher under an AV system in Arizona. Similarly, tomato production has been shown to be successful, with some studies reporting increased fruit quality and water productivity despite a potential slight reduction in total yield [22, 69, 83]. The timing of shading can also be critical; dynamic systems that track the sun can be programmed to provide shade during the hottest parts of the day while allowing more light during cooler periods, helping to optimize photosynthesis [27, 41].

Beyond yield, AV systems can affect crop quality. Forage quality under panels has been shown to remain higher later into the season in drylands, extending the grazing period for livestock [84]. For some fruits, such as apples and grapes, shading can reduce sunscald, delay ripening, and alter the chemical composition (e.g., sugar and acid content), which can be beneficial or detrimental depending on the desired characteristics [51, 60].

3.2.3. Livestock and Pasture Production

Agrivoltaics has proven highly synergistic with animal husbandry. The shade and shelter provided by the panels offer significant animal welfare benefits by reducing heat stress [29, 30, 91]. Studies have shown that sheep and cattle spend a significant amount of time resting in the shade of the panels on hot days, which reduces their water intake and core body temperature [29, 91]. This improved comfort can lead to better animal health and productivity.

Forage production under AV systems shows a similar pattern to crop yields. In water-limited environments, pasture biomass production can be equal to or greater than in open pasture due to water conservation [6, 72, 84]. Sturchio et al. [84] found that forage production was maintained in a semi-arid grassland, effectively doubling the productive output of the land when combined with the energy generated. Even when total biomass is slightly reduced, the extended growing season and improved forage quality can compensate for the lower quantity [3, 95]. Animal behaviour studies also indicate that livestock, such as sheep, readily adapt to grazing within AV arrays without negative impacts on their foraging patterns [6, 92].

3.3. Impact on Energy Generation

The agricultural component of an AV system is not merely a passive user of the land but actively interacts with the PV array, influencing its performance.

3.3.1. Energy Yield and System Performance

The energy yield of an AV system is primarily determined by its design (panel density, tilt, tracking) and the local solar irradiance. By definition, spacing panels out to allow for agriculture reduces the total installed capacity per unit of land compared to a conventional, high-density solar farm [14, 23]. Therefore, the total energy output per hectare from an AV system is lower. However, the key metric for evaluation is the Land Equivalent Ratio (LER), which measures the overall land productivity. Numerous studies have reported LER values significantly greater than 1.0, typically ranging from 1.10 to as high as 1.90 [1, 5, 58, 101]. An LER of 1.70, for instance, means that 1.7 hectares of separate monoculture (1 ha for farming, 0.7 ha for solar) would be needed to produce the same combined output as 1 hectare of the agrivoltaic system. This clearly demonstrates a significant improvement in land-use efficiency.

The choice of system design profoundly affects energy output. Bifacial panels, which can capture reflected light (albedo) from the ground, are particularly effective in AV systems, especially in vertical configurations [4, 24, 32]. The type of vegetation underneath can influence the albedo and thus the bifacial gain [37]. Single-axis tracking systems have also been shown to significantly boost energy production while allowing for dynamic light management for the crops below [4, 27].

3.3.2. Panel Temperature and Efficiency

A crucial synergistic benefit is the cooling effect of the underlying vegetation on the PV panels. Solar panels lose efficiency as their operating temperature increases [77, 80]. The process of evapotranspiration from crops and pasture creates a cooler, more humid microclimate around the panels compared to the bare ground or gravel found in conventional solar farms [34, 48]. This "biogenic cooling" can lower panel temperatures by several degrees Celsius. Williams et al. [79] modelled this effect and found that it could increase annual electricity production by about 1%. While modest, this gain in efficiency, coupled with a potential increase in the operational lifespan of the panels due to reduced thermal stress, adds to the overall economic value of the system. Kumpanalaisatit et al. [34] observed this effect experimentally with the cultivation of Bok Choy in Thailand, noting improved power generation efficiency.

3.4. Environmental and Economic Dimensions

Beyond the dual production of food and energy, AV systems offer a range of additional co-benefits and present a unique economic proposition.

3.4.1. Soil, Water, and Biodiversity

The long-term impact on soil health is a critical area of ongoing research. The reduction in temperature extremes and higher moisture retention under panels can foster a more stable environment for soil biota [33, 99]. However, construction activities and altered precipitation patterns (e.g., water runoff from panels creating drip lines) can lead to soil compaction and erosion if not managed properly [97]. Some studies have reported positive changes in soil organic carbon and microbial communities under AV arrays over several years [35, 96], while others have shown localized negative impacts [98]. The integration of restorative agricultural practices, such as planting native vegetation or cover crops, can further enhance soil health and biodiversity [2, 96].

The impact on biodiversity is also multifaceted. AV systems can provide habitat and resources for pollinators, especially in arid landscapes where the shade and moisture create floral refuges that last longer into the season [71]. The structures can also serve as perches for birds. However, the infrastructure can also fragment habitats. The overall ecological impact depends heavily on the initial state of the land (e.g., converting degraded pasture vs. a pristine ecosystem) and the management practices employed [21, 106].

3.4.2. Economic Viability and Social Acceptance

The economic case for agrivoltaics is complex. The initial capital cost of an AV system is higher than that of a conventional solar farm due to the need for elevated structures and more complex installation procedures [31, 66]. However, this is offset by the creation of a second revenue stream from the sale of agricultural products [1, 7]. The LER provides a strong biophysical argument for its value, and techno-economic analyses have shown that AV systems can be profitable, particularly for high-value crops or in regions with high electricity prices and supportive policies [1, 103]. Schindele et al. [31] demonstrated the economic feasibility of an AV system in Germany, finding it competitive with traditional agriculture.

Social acceptance is a key factor for the successful deployment of AV systems [9, 20]. By maintaining agricultural activity and preserving the rural landscape, agrivoltaics can often overcome the local opposition that frequently stalls conventional solar projects ("NIMBYism" - Not In My Back Yard). It provides a pathway for farmers to diversify their income, making their operations more resilient to climate and market volatility, and can help sustain farming livelihoods [20, 74]. The development of clear national guidelines and standards, such as those in Germany (DIN SPEC 91434) [105] and France [104], is crucial for providing regulatory certainty and ensuring that AV projects deliver genuine agricultural benefits rather than simply being "solar on stilts."

DISCUSSION

The results synthesized from over a hundred studies paint a compelling, albeit complex, picture of agrivoltaics as a promising solution for integrated land use. The findings demonstrate that AV systems can successfully produce food and energy simultaneously, often achieving a higher overall land productivity than separate monocultures [101, 108]. This discussion will critically analyze the key synergies and trade-offs revealed by the evidence, place them within the broader context of sustainable development, identify crucial knowledge gaps, and suggest directions for future research.

4.1. Synthesis of Findings: A Symbiotic System

The core strength of agrivoltaics lies in its ability to transform a competitive relationship over land into a symbiotic one. The most significant mechanism driving this synergy is the moderation of the microclimate by the PV array [39, 44, 50]. By providing partial shade, the panels buffer the agroecosystem against environmental stressors, particularly excessive solar radiation and heat. This effect is most beneficial in arid, semi-arid, and increasingly, in temperate regions experiencing more frequent heatwaves and droughts due to climate change [70]. The resulting improvement in water availability is a critical co-benefit, directly enhancing crop water productivity [22, 46] and making agriculture viable in previously marginal lands. This finding repositions agrivoltaics not just as a land-saving technology, but as a climate adaptation strategy [16, 28].

Simultaneously, the agricultural component provides a tangible benefit to the energy system. The biogenic cooling effect, while modest in terms of percentage gains in energy efficiency [79], is a consistent and valuable synergy. When scaled across large installations over a 25-30 year lifespan, even a 1-2% increase in energy output and the potential for extended panel longevity due to reduced thermal degradation can translate into significant economic and environmental gains [34]. This reciprocal relationship—panels protecting crops, and crops cooling panels—is the fundamental principle that elevates agrivoltaics above simple co-location.

The consistently high Land Equivalent Ratio (LER) reported across numerous studies [1, 5, 53, 58] serves as the most powerful quantitative evidence of the system's enhanced efficiency. An LER of 1.5 implies a 50% increase in land productivity, a remarkable gain in a world of finite resources. This metric validates the core premise of agrivoltaics: that the whole can be greater than the sum of its parts.

4.2. Navigating the Trade-offs: Light, Yield, and Optimization

Despite the clear synergies, agrivoltaics is not a universally applicable panacea. The primary trade-off is the reduction in Photosynthetically Active Radiation (PAR) reaching the crops. For any given location, there exists a fundamental compromise between energy generation (which favours higher panel density) and agricultural production (which requires sufficient light) [23, 88]. The extensive body of research clearly shows that there is no one-size-fits-all solution; the optimal balance is highly specific to the crop, climate, and economic goals.

The variability in crop yield responses is the most telling illustration of this trade-off. While shade-tolerant leafy greens often thrive [56], the yield of sun-loving staple crops like wheat and corn can be compromised, particularly in cooler, light-limited climates [8, 59, 89]. This highlights the critical importance of site-specific design and crop selection. The future of agrivoltaics likely lies not in retrofitting existing agricultural systems but in co-designing new, integrated systems where the PV layout is optimized for a specific crop's light requirements, and crop varieties are selected or even bred for shade tolerance [93, 94].

The emergence of advanced AV technologies offers pathways to mitigate this trade-off. Dynamic systems with tracking capabilities can modulate the light environment throughout the day or season, providing shade when it is most needed (e.g., midday to prevent heat stress) and allowing full sun when light is more valuable for photosynthesis (e.g., morning and evening) [27, 41, 62]. Likewise, innovations in PV technology, such as semi-transparent or wavelength-selective modules, aim to share the solar spectrum more efficiently, transmitting PAR wavelengths vital for photosynthesis while absorbing others for electricity generation [25, 54, 67]. While currently more expensive, these technologies represent a frontier for maximizing system synergy and minimizing yield trade-offs.

4.3. Broader Implications and Future Research Directions

The successful implementation of agrivoltaics at scale has implications reaching far beyond the farm gate. It contributes directly to several of the UN Sustainable Development Goals, including Zero Hunger (SDG 2), Affordable and Clean Energy (SDG 7), Climate Action (SDG 13), and Life on Land (SDG 15) [16, 108]. By providing farmers with a diversified and stable income source, it can enhance the resilience of rural economies [74]. By reducing land-use conflicts, it can accelerate the deployment of renewable energy needed to meet climate targets [12].

However, to realize this potential, several key knowledge gaps must be addressed by future research:

1. Long-Term Ecological Impacts: Most AV studies are short-term (1-3 years). There is a pressing need for long-duration (10+ years) monitoring of AV sites to understand the cumulative impacts on soil health (carbon sequestration, nutrient cycling, compaction), hydrology, and local biodiversity [33, 97, 99]. Are the observed benefits in soil moisture and microbial health sustained over time? What are the long-term shifts in plant and animal communities?

2. Optimized System Co-Design: Research should move from testing existing PV layouts over crops to an integrated co-design approach. This requires interdisciplinary collaboration between agronomists, engineers, and economists to develop sophisticated models that can optimize system configuration (panel height, density, orientation, technology) for specific crop-climate-market combinations [27, 42, 73, 89].

3. Breeding for Agrivoltaics: A largely unexplored frontier is the development of "shade-adapted" crop varieties. Conventional breeding has overwhelmingly selected for performance in full-sun conditions. A targeted breeding program could develop cultivars that maintain high yields and quality in the unique, light-limited, but less stressful microclimate of AV systems [93, 94].

4. Scaling and Socio-Economics: More research is needed on the socio-economic drivers and barriers to adoption at scale. This includes detailed techno-economic analyses across a wider range of agricultural systems and markets [66, 103], studies on consumer perception of "agrivoltaic-grown" products, and analysis of policy mechanisms (e.g., subsidies, zoning regulations, carbon credits) that can best support sustainable and equitable deployment [9, 20].

5. Expanding Geographic and Agricultural Scope: While research is growing, it remains concentrated in a few regions and on a limited set of crops. More studies are needed in tropical and subtropical regions of the Global South, where the potential for both solar energy and agricultural improvement is immense [19, 20]. Furthermore, applications beyond traditional cropping, such as aquaculture (aquavoltaics) or integration with specialty crops like medicinal plants [62], warrant further investigation.

4.4. Limitations of the Review

This review, while comprehensive, has several limitations. First, the narrative synthesis approach, while necessary given the heterogeneity of the studies, precludes a quantitative meta-analysis, which could provide more precise estimates of effect sizes. Second, a potential publication bias may exist, where studies showing positive or significant results are more likely to be published than those with null or negative findings. Finally, the rapidly evolving nature of the field means that new research is constantly emerging, and any review is a snapshot in time. Despite these limitations, the synthesis provides a robust and evidence-based overview of the current state of knowledge in agrivoltaics.

CONCLUSION

Agrivoltaics stands at a critical juncture, evolving from a niche concept into a mainstream contender for sustainable land management. This comprehensive review of 108 studies confirms that the dual-use of land for agriculture and solar energy generation is not only technically feasible but also highly synergistic. The evidence overwhelmingly shows that AV systems can lead to a significant increase in overall land productivity, as demonstrated by Land Equivalent Ratios consistently exceeding 1.0. The core benefits are driven by a modified microclimate under the panels, which enhances water conservation and protects crops and livestock from environmental stress, while the agricultural understory, in turn, provides a cooling service to the PV panels, boosting their efficiency.

The findings highlight that the success of an agrivoltaic system is not automatic but hinges on intelligent, context-specific design. The trade-off between light for crops and light for energy is real, necessitating a careful balancing act that considers the local climate, the physiological needs of the chosen crop or animal, and the economic objectives of the farmer. The future of agrivoltaics lies in moving towards this sophisticated co-design, supported by dynamic systems, advanced PV technologies, and potentially, new crop varieties bred for performance in partial shade.

By mitigating land-use conflicts, enhancing climate resilience in agriculture, and contributing to rural economic diversification, agrivoltaics offers a tangible pathway toward achieving multiple sustainable development goals simultaneously. To unlock its full potential, the research community must now focus on long-term ecological monitoring, interdisciplinary system optimization, and addressing the socio-economic barriers to adoption. For policymakers and investors, the challenge is to create supportive frameworks that encourage the development of genuine, symbiotic agrivoltaic systems, ensuring that they contribute meaningfully to both a stable food supply and a clean energy future. Agrivoltaics is more than just solar panels on a farm; it is a reimagining of the landscape as a high-efficiency, integrated system for a sustainable world.

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