

Review

Opportunities, Technological Challenges and Monitoring Approaches in Agrivoltaic Systems for Sustainable Management

Carmine De Francesco , Luana Centorame , Giuseppe Toscano  and Daniele Duca 

Department of Agricultural, Food and Environmental Sciences, Marche Polytechnic University, Via Brecce Bianche, 60131 Ancona, Italy; c.defrancesco@univpm.it (C.D.F.); g.toscano@univpm.it (G.T.)

* Correspondence: l.centorame@pm.univpm.it (L.C.); d.duca@univpm.it (D.D.)

Abstract: In the context of climate change and the increasing demand for innovative solutions in agriculture and energy, agrivoltaic systems (AVSs) have emerged as promising technologies. These systems integrate photovoltaic panels with agricultural practices, optimizing both food and energy production. This study provides a comprehensive review focused on monitoring techniques applicable to AVS, including fixed sensors and remote monitoring tools. Bibliographic analysis revealed a significant increase in scientific interest in AVSs since 2019, with most publications focusing on technological, agronomic, and environmental aspects. Key findings highlight environmental benefits such as reduced greenhouse gas emissions, improved water efficiency, and enhanced soil quality. Otherwise, challenges including high initial costs and the persistence of technical complexities. Innovative configurations such as semi-transparent or vertically bifacial panels enable resource optimization and improved agricultural yields if combined with advanced monitoring systems. This study highlights the importance of incentive policies and further research to maximize the potential of AVSs in promoting sustainable land management.

Keywords: photovoltaic; sensor; sustainability; agronomy; sustainable energy; agriculture and photovoltaics; dual-use land; agricultural innovation



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1. Introduction

Today, humanity is called to face the growing demand for energy and food with the need to mitigate climate change and protect natural resources [1]. Climate change, amplified by human activities, is already having a dramatic impact on global agriculture, increasing the incidence of extreme weather events. Moreover, traditional fossil-fuel based energy production contributes significantly to greenhouse gas emissions, placing additional pressures on global ecosystems [2,3].

In this context, AVSs emerge as an innovative solution to address these interconnected challenges. An AVS is a dual-use agricultural setup where land is used to both grow crops and generate solar energy. This helps in transforming lands into multifunctional systems capable of simultaneously generating renewable energy and producing food [4–9]. AVSs are designed to improve land efficiency, enhance resource use, and support sustainable agriculture by reducing energy costs and potentially protecting crops from excessive heat or drought [10,11].

To meet the growing global demand for food and energy, AVSs respond directly to the United Nation Sustainable Development Goals [12]. Their ability to promote integrated solutions makes them particularly relevant when global resources are increasingly limited. The large-scale adoption of AVSs would not be possible without significant regulatory

developments, which have progressively supported their development [13]. Since the early 2000s, governments and international organizations have recognized the potential of AVSs in contributing to climate and energy security goals by developing specific regulations and incentive programs [14].

In Europe, the European Green Deal is a key reference point for green transition policies, promoting the integration of renewable energy with agriculture [15,16]. Within this framework, the Farm to Fork strategy emphasizes the importance of sustainable agricultural practices, integrating technologies, such as AVSs, to reduce emissions, improve agricultural resilience, and preserve biodiversity. Several member states, including Italy, France, and Germany, have introduced specific financial incentives to promote the adoption of AVSs [17].

The potential of agri-food has also been rapidly recognized in Asia [18,19]. China is a world leader in solar energy production and has initiated several large-scale projects, often in arid or desert areas, to exploit the combined benefits of renewable energy and agricultural resilience [13,20]. In Japan, the limited availability of agricultural land has made AVS technology a strategic means of joining together food and energy production.

In the United States, the AVS sector received a major boost through the Inflation Reduction Act (IRA) of 2022, which allocated billion dollars to promote renewable energy and innovative agricultural technologies [21].

Technical advances have transformed AVSs into highly adaptable and sophisticated solutions that meet the specific needs of different climatic and agronomic contexts [22,23]. Configurations of AVSs range from traditional fixed panels to advanced solutions such as semi-transparent panels, double-sided vertical panels, and solar tracking systems [24–30].

Monitoring is an essential component in the optimization of AVSs [31,32]. Internet of Things (IoT), sensors, drones, and satellite images are used to collect real-time data on parameters such as solar radiation, soil moisture, temperature, and plant health. These data enable adaptive resource management, improving overall efficiency and ensuring long-term sustainability [33–35]. Furthermore, advanced monitoring is crucial for minimizing long-term environmental and health effects [32].

AVS plants offer significant environmental benefits, contributing directly to climate change mitigation and the promotion of sustainable agriculture [36]. A crucial advantage of AVSs is their ability to reduce greenhouse gas emissions by replacing fossil fuels with solar energy [37]. Furthermore, the microclimate created by the panels reduces water evaporation from the soil, improving water efficiency. This is critical in arid regions [38].

AVSs protect crops from extreme weather conditions, such as heat waves and droughts. The shading provided by the panels reduces heat stress. In addition, the higher relative humidity under the panels promotes the growth of sensitive crops [18,39].

The social and micro-climatic aspects of AVSs are analyzed less by academics, probably due to the inherent difficulties in measuring their impacts in a systematic way and the complexity of these dimensions. For example, social aspects involve subjective factors, such as community perceptions, social acceptance, and behavioral dynamics, which are more difficult to quantify and model [40–43]. Similarly, microclimate studies require high-resolution localized data and advanced methodologies to capture small-scale variations, making research in this area particularly resource-intensive [44–47].

The current review aims to provide a detailed and interdisciplinary overview of AVSs, analyzing technical and environmental developments through an in-depth analysis of the available scientific literature and applications in projects. The opportunities and challenges of this technology are explored, focusing on advanced monitoring techniques and their relevance to sustainable management. As highlighted by authors, sustainability is an

unexplored issue. Finally, the article will offer recommendations for future research and policy, highlighting the crucial role of AVSs in building a sustainable future.

2. Materials and Methods

A complete review of scientific publications was carried out using Web of Science (Clarivate Analytics, Philadelphia, Pennsylvania, United States, accessed on 15 September 2024), Scopus (Elsevier, Amsterdam, Netherlands, accessed on 15 September 2024), and Google Scholar (Google, Mountain View, California, United States accessed on 15 September 2024).

The literature for the review analysis was acquired up to 15 September 2024, considering different categories of scientific publications (articles, reviews, and conference papers). Relevant keywords were used in the search, such as “agrivoltaics”, “agrovoltaics”, “photovoltaics in agriculture”, “renewable energy and agriculture”; these were combined with terms such as “effectiveness”, “sustainability”, “integration”, “technology”, and “benefits”. Furthermore, the search period was set to run from the 2000s. In addition to academic research papers, and in order to include current research and development work on AVSs, the search scope was expanded to include the most significant commercial-scale demonstration papers from industry and international conferences in the field, and to include highlights of current legislation and technical aspects that do not directly address the AVS topic but which are indirectly related to it.

As shown in Table 1, the first identification phase yielded a total of 306 scientific publications using the same keywords. Of these, 159 were obtained from the Web of Science, 125 were obtained from Scopus, and 22 came from Scholar. In the second step, all articles were entered into an Excel spreadsheet, including title, abstract, year of publication, journal, authors, and DOI. We removed all duplicates, all publications not related to the topic, all articles not written in English, and all articles that were not available. A total of 195 were selected. The next step consisted of identifying papers fully focused on the topic and available for full text reading. Finally, a total of 132 scientific publications were selected.

Table 1. Articles identified and screened for review.

	Identification	Screening	Total
Web of Science	159	58	132
Scopus	125	54	
Scholar	22	20	

All the selected articles were identified and imported into a Mendeley reference manager. Subsequently, the coding and classification process allowed for a clearer categorization by differentiating based on the type of publication, the main focus, detailed sub-categories, the scale of analysis, crop type, the geographic scope, and the year of publication.

- Type of publication: classify as research article, review, or conference paper.
- Main focus: sensors, technology, agronomy, spatial analysis. We include any other significant categories found in the dataset.
- Detailed sub-categories: break down the main themes into specific subcategories. Examples of themes include the following areas:
 - Social impact (studies addressing social acceptability, community engagement, and workforce implications);
 - Environmental impact (includes soil health, biodiversity, water use, etc.);
 - Microclimatic factors (humidity, temperature variations, etc.);
 - Economic aspects (cost–benefit analyses, market implications, funding sources);
 - Agronomic details (yield, crop health, planting methods);
 - Technological innovations (hardware and software used, innovative methods);

- Energy efficiency (energy consumption, sustainable practices).
- Scale of analysis: classify into single project case study or global analysis.
- Crop type: catalog specific crops analyzed (e.g., wheat, corn, rice) or, if applicable, multi-crop studies.
- Geographic scope: record the country/state/region where the research was conducted, if provided.
- Publication year: for a chronological perspective.

This refined classification added clarity, emphasized the specific impacts of the research, and facilitated a focused understanding of the data. In addition, this classification was the basis for making it easier to obtain the results of the literature analysis.

3. Results

The most effective overview of the selected literature arises from a systematic evaluation of the previously described classification, with detailed analysis of individual subsections and all categorized items. This process highlights key thematic areas in AVS research, emphasizing the prominence of technical, agronomic, environmental, and socio-economic aspects. The “technology” and “agronomy” categories are the most represented, reflecting a strong focus on innovation and the optimization of agricultural practices. Meanwhile, environmental impacts are gaining attention, though economic and social dimensions remain underexplored. Monitoring emerges as a critical aspect of sustainable management, enabling real-time data collection on parameters such as solar radiation, soil moisture, and plant health. These tools facilitate adaptive management strategies, enhancing resource efficiency and ensuring long-term sustainability.

3.1. Bibliographic Analysis

The results of the bibliographic analysis highlight the importance of the proper classification of documents to ensure effective and targeted access to information. Accurate classification allows content to be organized systematically, facilitating the retrieval of relevant data and optimizing search time. In addition, well-structured cataloging helps to improve the transparency and reproducibility of research, promoting a solid foundation for future investigations. Finally, proper classification facilitates the interpretation of results, enabling a more comprehensive and integrated analysis of existing information.

3.1.1. Type of Publication

The types of scientific papers analyzed were different. They were classified into articles, reviews, and conference papers. As shown in Figure 1, the most represented type was scientific articles, with 81.54% of the total, followed by review and conference papers, respectively, with 10.77% and 7.69% of the total.

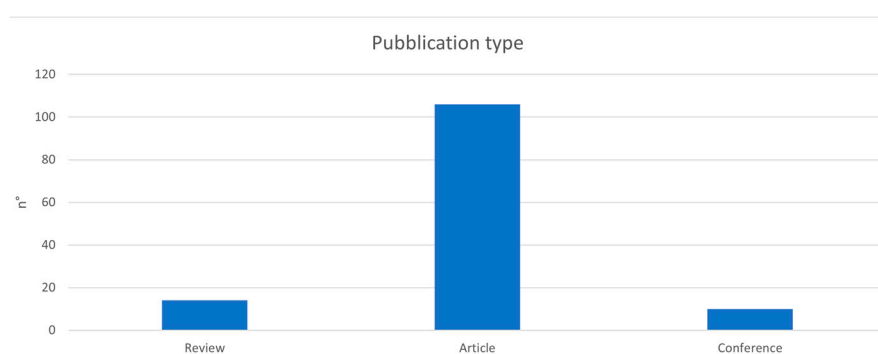


Figure 1. Classification of publication type.

3.1.2. Main Focus

Figure 2 shows the distribution among the main categories identified. In fact, for the proper management of the articles, 4 categories were identified in order to distinguish them according to their main focus. In detail, the most represented categories are those that include technological and agronomic topics, followed by the topics of land analysis. In several cases, a big difference was found for sensors that were covered. This can be explained by the facts that this is a newly developed field and experimentation can often take several years.

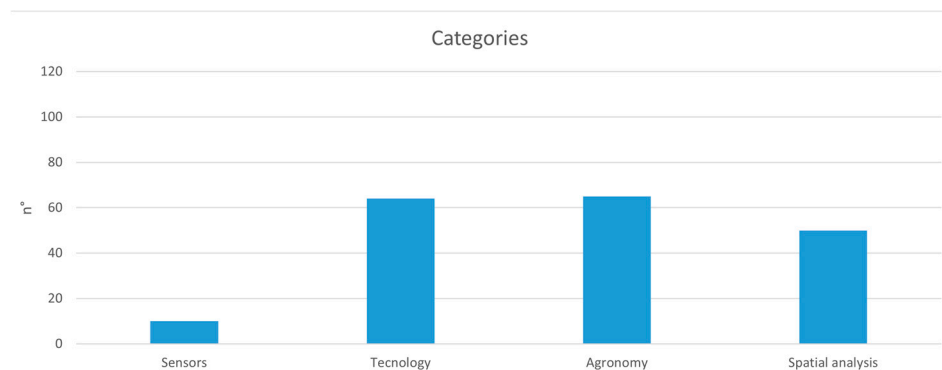


Figure 2. Classification in categories.

3.1.3. Detailed Sub-Categories

Figure 3 specifies which sub-category is covered by the available literature, offering a detailed view of the areas receiving the most research attention. The sub-categories include social, environmental, microclimatic, economic, agronomic, technological, and energetic areas. Each one reflects a specific aspect of AVS studies.

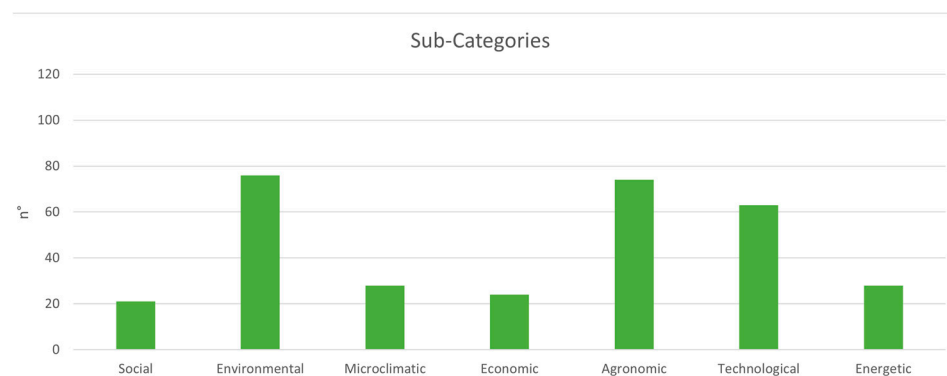


Figure 3. Classification in sub-categories.

The distribution highlights a strong interest in certain aspects of research over others. Notably, the “environmental” sub-category leads with the highest number of articles, demonstrating a strong focus on the environmental implications of AVS. This is closely followed by “agronomic” and “technological” sub-categories, which show that there is significant research on agricultural management practices and integration with photovoltaic technologies. Conversely, sub-categories such as “social”, “microclimatic”, “economic”, and “energetic” have fewer articles, suggesting these areas have been explored to a lesser extent. In particular, the sub-category “microclimatic” was found to have been little explored, as the research focused mainly on the environmental conditions under the microclimate created by the panels.

The graph highlights the importance of environmental, agronomic, and technological factors that are considered highly relevant or promising for advancing AVS research. It can be seen that they are more studied than other aspects of this topic.

3.1.4. Scale of Analysis

Figure 4 illustrates the distribution of scientific articles on AVSs. These are categorized by the scale of analysis being either global or local. Out of 132 articles reviewed, 34 adopt a global perspective, while 98 focus on local contexts. This distribution reveals a significant disparity, with local-scale studies accounting for 75% of the total, indicating a strong focus on region-specific research.

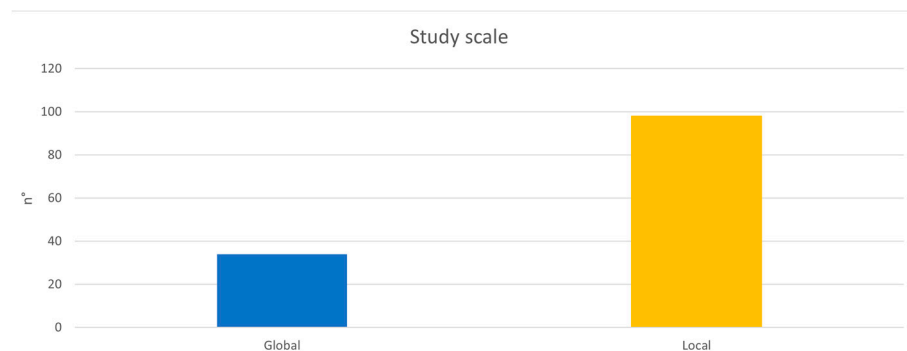


Figure 4. Scale of analysis.

The predominance of local studies suggests that AVS research often targets the unique characteristics of specific regions, communities, or agricultural zones. This localized approach likely stems from the need to tailor AVS solutions to each area's distinct climatic, environmental, and socio-economic conditions, making the findings more relevant and applicable to local needs. Conversely, the 34 articles that take a global approach represent only 25% of the total, offering a broader perspective on AVS challenges and opportunities. These studies tend to develop models and strategies with international applicability, addressing overarching themes that can be adapted across different contexts. The lower number of global studies, however, suggests that more research is needed to systematically compare and analyze the large-scale potential and limitations of AVSs.

Figure 5 illustrates the global distribution of scientific studies on local AVS projects across various countries. Of the total analyzed studies ($n = 98$), 69 articles (70.4%) identified the location of their experimental project. The color intensity on the map reflects the concentration of studies: darker shades indicate a higher concentration, while lighter shades represent a smaller presence.

The United States and China, shown in the darkest shades, are responsible for the highest percentages of studies, 16% and 14%, respectively. This suggests that there is strong interest and significant research activity on integrating AVSs in these countries, which is likely due to their extensive agricultural areas and the focus on developing sustainable energy and agricultural practices. A fair number of studies have been carried out in Europe, with represented countries contributing between 1% and 7% of the total; for example, Italy and Sweden have the highest percentages. Overall, the European landscape achieves a representation of studies comparable to both the United States and China, demonstrating a significant interest in the subject. India and Japan show a moderate study rate, reflecting a growing interest in AVS projects, although their numbers are still lower than those in China and the United States. In contrast, many countries in Africa, South America, and most of Asia are shaded in gray, indicating a limited number of published scientific studies on local AVS projects or their absence.

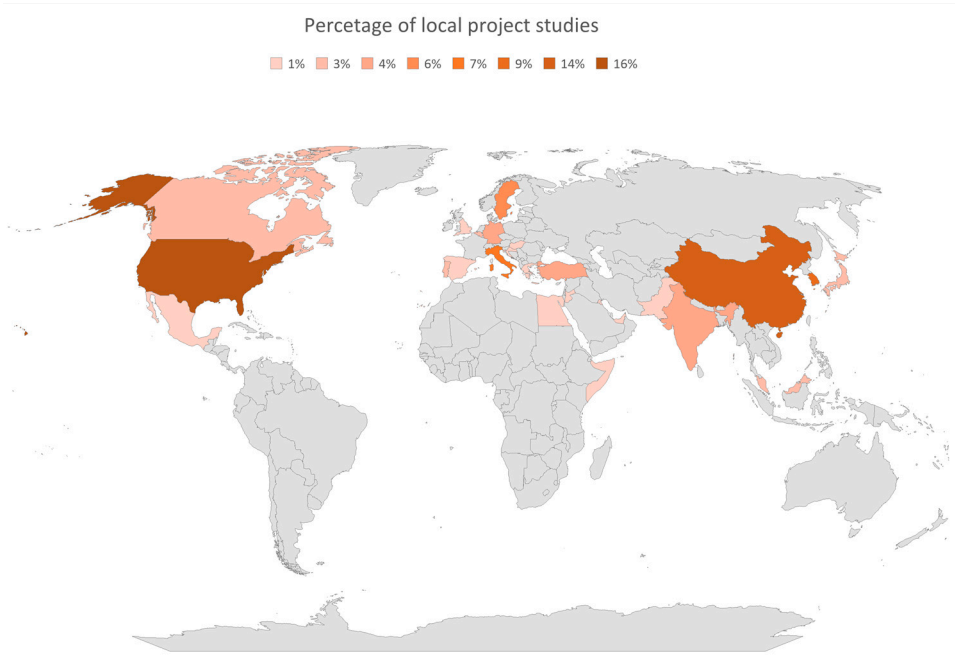


Figure 5. Spatial distribution of local projects.

3.1.5. Crop Type

Figure 6 shows the distribution of crops examined in scientific articles on AVSs, indicating the percentage representation of each crop among the 50 articles (out of 98 total) that specifically mention types of plants or agricultural systems.

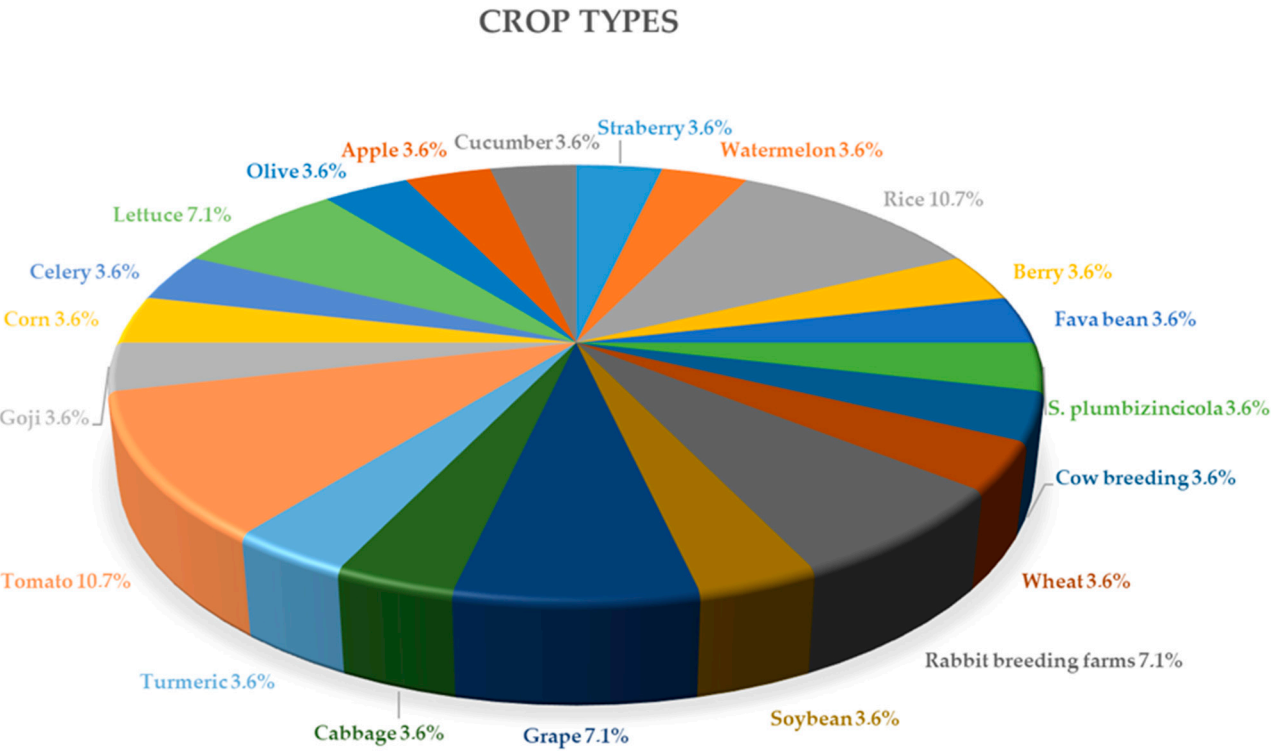


Figure 6. Classification of crops type analyzed in a local-scale analysis.

The data reveal that 51% of the articles conducted at a local scale focus on particular crops, suggesting that AVS research primarily addresses broader issues, often not conducting detailed analyses of individual crops. The most represented category is “various crops

reported”, accounting for 44% of the articles. This broad grouping may reflect an interest in assessing the impacts of AVSs across multiple crops simultaneously or may be part of a research approach that seeks general findings that are applicable to a variety of plant types. However, by covering multiple crops collectively, these studies may limit insights into the specific effects of AVSs on individual crops.

The pie chart shows highlights of the crops analyzed individually, accounting for 56% of the 50 articles that specified a crop. From this, we can see that tomatoes and rice are the most studied plants, each appearing in 11% of the articles. This focus may reflect the wide distribution of these crops and their potential to benefit from photovoltaic (PV) systems. Tomatoes, sensitive to extreme temperatures, could benefit from reduced heat stress under PV panels. In addition, rice is a water-intensive crop and could benefit from the cooling effects provided by partial shading.

Lettuce and grapes, as well as rabbit farming, appear in 7% of cases. Grapevine is a high-value crop and can be studied for improved quality and yield through AVS shading, which could help to moderate environmental stresses on the vine. Lettuce is a short-cycle crop and could be compatible with AVSs because of its rapid growth, which allows for multiple yields in a single growing season. Other crops, including strawberries, watermelons, berries, fava beans, soybeans, cabbage, turmeric, olives, apples, cucumbers, and goji, are mentioned in only 4% of the articles, indicating limited interest. The low presence of these crops could result from their lower global prevalence or perceived poor compatibility with AVSs.

Lastly, livestock breeding and the cultivation of *S. plumbizincicola* (a plant used for phytoextraction) are under-studied, suggesting that AVS research has not yet extensively covered livestock breeding or plants for specific uses.

3.1.6. Journals and Years of Publication

Figure 7 depicts the trend in scientific publications on AVSs over the years, spanning the years from 2000 to 2024. It is clear that there is a strong and increasing interest in AVS. Between 2000 and 2018, the number of publications was minimal, with only a few articles published each year. This period reflects exceptionally low interest in this subject, because the development of AVSs was still an unknown or underdeveloped discipline. The limited research performed during these years suggests that the topic had yet to gain traction due to a lack of awareness or the technological constraints that limited exploration.



Figure 7. Publications over the years.

From 2019 onward, there was a clear shift. The amount of publications began to rise, underlining a growing interest and increased research activity. However, it is from 2020 onwards that this growth became exponential, with a sharp increase in publications that continued to accelerate over the following years, reaching a peak in 2024. This peak indicated a heightened focus on AVSs within the scientific and technological communities, driven by increasing awareness of energy sustainability and the potential for integrating agriculture with renewable energy.

Figure 8 analyses the distribution of these publications across different scientific journals. Each journal contributes to the topic to varying extents, reflecting the multidisciplinary nature of AVSs.

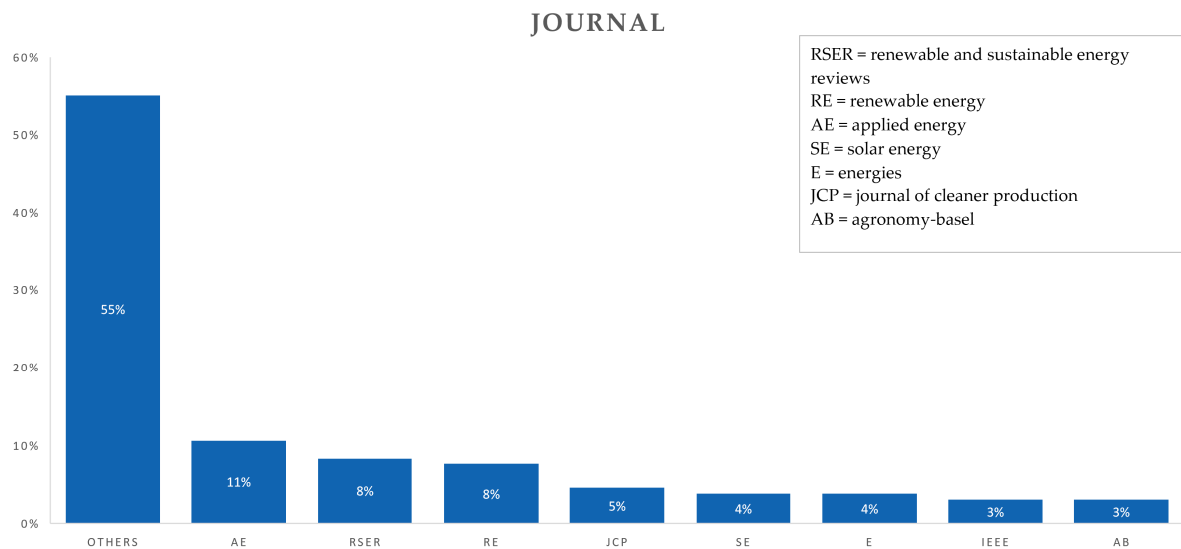


Figure 8. Journal classification.

Applied Energy is the most represented journal, accounting for 11% of the total publications. This journal primarily focuses on research related to renewable energy and energy applications, making it a suitable platform for AVS studies. *Renewable Energy* and *Renewable and Sustainable Energy Reviews* follow with 8% of the publications, indicating significant interest in the application of sustainable energy as applied to agriculture. The *Journal of Cleaner Production* represents 5% of the publications, highlighting the relevance of AVSs in the context of sustainable and clean production practices. Other journals, such as *Solar Energy* and *Energies*, contribute between 3% and 5% each, showing that AVSs are also addressed within the broader realm of renewable energy and sustainability. *Agronomy* (Basel) is a journal specifically focused on agronomy and accounts for 3% of publications, illustrating the agricultural sector's interest in AVSs in strategies for integrating energy production into agricultural land management.

The “others” category makes up 55% of the publications. This substantial figure suggests that a generous portion of AVS research is published across a diverse array of journals, many of which are less specialized or take a more interdisciplinary approach to the topic. The high percentage in “others” may also reflect the broad range of disciplines involved in the study of AVSs, which intersects with fields like energy, agronomy, ecology, and engineering.

3.2. Technical Analysis

AVSs require complex and multidisciplinary design in order to optimize energy and agricultural production, maximizing the synergy between the two activities. Technical

characteristics vary depending on the type of plant, materials used, configuration, and monitoring tools.

AVSs use a variety of photovoltaic panels, each designed to adapt to crop needs and environmental conditions.

Traditional fixed-tilt panels are ideal for static installations. They are easier to implement but limit adaptation to variable solar radiation. Panel density must be carefully calculated to avoid excessive shading on crops [48,49]. Panels are installed over crops, providing uniform shading. They require raised supports, and special attention must be paid to drainage and access for agricultural activities [49,50].

Vertical bifacial panels collect solar radiation on both sides, taking advantage of both direct and reflected light. These panels are particularly effective in environments with high diffuse radiation and reduce conflict for land use by leaving free space between rows [48,51]. The panels are installed in vertical rows, creating bands of light and shade. This configuration is less invasive to agriculture and more suitable for crops with low light requirements [51–53].

Tracking systems allow panels to follow the sun, maximizing energy production during the day. Optimized tracking systems balance energy and agricultural needs by adjusting the tilt to avoid excessive shading [54–56].

AVS greenhouses enable the optimization of agricultural yields through a controlled microclimate and the use of semi-transparent panels that modulate sunlight [57,58]. The use of glass-silicon panels ensures high fruit quality and agricultural yields comparable to greenhouses without panels [58]. In addition, smart greenhouse systems can adapt light and climate to promote the growth of sensitive crops [57,59].

Recent advances in photovoltaic technology have led to the development of innovative modules for AVSs, including monocrystalline, polycrystalline, organic, and semi-transparent panels.

Monocrystalline modules, made from a single silicon crystal, offer high conversion efficiency (18–22%) and are particularly suitable for installations with limited space. However, they require strategic arrangement to prevent the excessive shading of crops [48,49].

Polycrystalline modules, produced by fusing silicon crystal fragments, have a lower conversion efficiency (15–17%) but promote a more uniform light distribution, reducing light stress on underlying crops [50,56].

Technological evolution has also introduced modules made of organic and advanced materials, which are designed to overcome the limitations of crystalline silicon. Organic photovoltaic (OPV) panels are based on conductive polymers or small organic molecules and offer conversion efficiencies of 5–10% and high selective transparency, allowing the passage of photosynthetically active radiation (PAR), which is essential for crops [60,61].

Semi-transparent panels are made of advanced materials like amorphous silicon. They allow the balancing of energy generation with light transmission, achieving up to 15% efficiency and adjustable light transmittance between 20% and 50% [62,63]. The semi-transparent form was used to improve the transmission of light and was useful for photosynthesis. These panels make it possible to optimize crop growth by protecting them from light stress [60,61]. Semi-transparent panels offer significant scalability thanks to their versatility across various agricultural applications. AVSs in greenhouses use semi-transparent panels to regulate indoor lighting and temperature, improving agricultural yield and reducing energy consumption [50,63,64]. In open fields, they enable dual land use by shielding crops from extreme weather conditions while simultaneously producing energy [60,61]. Additionally, their modular design makes them ideal for small-scale urban farming, where space efficiency and adaptability are crucial.

Emerging technologies include beam-splitting modules, which separate wavelengths usable for photosynthesis from those used for electricity generation, maximizing the combined efficiency of agricultural and energy systems [65]. Additionally, organic thin-layer panels, combining organic and inorganic materials, improve stability and transparency, making them ideal for high-value AVS applications such as ornamental or medicinal plant cultivation [57].

AVSs are designed to achieve an efficiency of 15–25%, with potential increases occurring thanks to tracking systems [54,55]. The combination with batteries or storage systems allows excess energy to be stored for future use, ensuring greater stability in the supply [66].

Table 2 summarizes the key characteristics of the different photovoltaic technologies described above, providing a clear and intuitive overview of their performance, cost, and compatibility. The values given, such as efficiency and annual degradation rate, are expressed in ranges (e.g., 15–22%) to indicate variations related to factors such as material quality, operating conditions, and installation. In addition to reporting ranges, transparency is also specified with values such as ‘variable by layout’ as it may depend on the design and orientation of the system. The ‘+’ symbols in the table represent the intensity of the parameter considered: as the number of symbols increases (e.g., +, ++, etc.), the parameter becomes more significant or relevant. For example, a ‘+’ under the cost column indicates that the cost is low or moderate, while more ‘+’s would indicate an increasing value or greater impact. The AVS compatibility column follows the same principle, with a ‘+’ denoting basic compatibility, increasing as the ‘+’ symbols increase. Finally, bibliographical citations provide key references to further the reporting of information.

Table 2. Characteristics and performance of photovoltaic systems and solar panels.

	Technology	Description	Efficiency	Transparency	Annual Degradation Rate	Cost	AVS Compatibility	Citations
Photo-voltaic system	Traditional fixed panels	Static installations, easy to install.	15–22%	variable by layout	0.3–1%	+	+	[48–50,67]
	Vertical double-sided panels	They collect light on both sides, using both direct and reflected light.	10–20%	variable by layout	0.3–1%	++	++	[48,51–53]
	Tracking systems	They maximize energy production during the day.	15–30%	variable by layout	0.3–1%	++ (single axis) +++ (double axis)	++	[54–56]
	Greenhouses	They optimize harvests with a regulated microclimate	5–15%	variable by layout	0.5–1%	++++	+++	[57–59,63,64]
Photo-voltaic panels	Monocrystalline	Produced with a single crystal of silicon	18–22%	~0%	0.3–0.7%	++	+	[48,49,67,68]
	Polycrystalline	Produced by fusing fragments of silicon crystals	15–17%	~0%	0.4–0.8%	+	+	[50,56,67,68]
	Organic (OPV)	Based on conductive polymers or small organic molecules	5–15%	20–50%	1–3%	+++	++	[60,61,69]
	Semi-transparent	Made from advanced materials such as amorphous silicon	15%	20–40%	0.5–1%	++++	+++	[50,60–63,69]
	Beam-splitting	They separate wavelengths.	upgrade of 5–15%	selective transparency	0.5–1%	+++++	+	[65,70]
	Organic thin layer	They combine organic and inorganic materials.	5–15%	50–90%	1.5–4%	++++	+++	[57,69]

3.3. Agro-Environmental Analysis

AVSs combine agricultural production with energy generation on the same land, optimizing land use and improving both agricultural and energy sustainability. These systems are gaining increasing global attention, especially in drought-prone areas [71–73]. The studies reported in this review explore the various effects of using crops, such as tomatoes [74–76], rice [77–79], lettuce [47,80,81], grape [82,83], and others. They provide a comparison between different crops in terms of yield and production under photovoltaic panels configured in AVSs [41,45,84–103].

A key component of these systems is agronomic monitoring, which involves the installation of microclimate sensors below the photovoltaic panels [85,104]. These tools enable the real-time data collection on key parameters such as solar radiation, soil moisture, temperature, and plant physiology. These data allow the optimization of crop growth by addressing specific needs, improving both agricultural productivity and the system's energy efficiency.

Recent studies have shown that partial shading can preserve crop quality while reducing water and thermal stress [11,85]. This benefit is particularly evident in shade-tolerant crops such as lettuce, tomatoes, and peppers, compared to more traditional crops like corn, soybeans, and wheat, which are less shade-tolerant [77,84,96,97,105–107]. However, results vary significantly depending on the crop type and the level of radiation in the environment [108].

AVS conditions foster increased air humidity which, in turn, contributes to improved soil moisture [85,86]. Studies on arable and horticultural crops have shown that AVSs can maintain higher soil moisture levels at various depths compared to reference areas in open fields [95]. This benefit is crucial for supporting crop growth in environments with limited water availability.

AVSs significantly influence crop physiological and morphological traits, such as the Leaf Area Index (LAI), Specific Leaf Area (SLA), and plant height. For example, LAI quantifies the leaf surface area available to capture PAR, which is essential for photosynthesis. A higher LAI improves a plant's capacity to intercept light, fostering growth. Otherwise, an excessive LAI can reduce light availability for lower-canopy leaves. Optimizing its value is the key to maximizing PAR efficiency in both agriculture and AVSs. Shaded conditions in these systems often lead to increased LAI and SLA, enhancing the plant's light interception ability. This increase not only supports plant growth but also aids in soil conservation by reducing erosion and improving water retention [109–111].

Another important aspect is the ability of AVSs to positively influence the local microclimate. Several studies have shown that the shading provided by solar panels can significantly reduce heat stress on livestock, improving their well-being during hot and sunny days [46,112–115]. Furthermore, evaporative cooling plays a critical role in lowering the surrounding ambient temperature, which also reduces the temperature of the photovoltaic panels.

In some cases, significant reductions in air temperature are observed, with daily fluctuations of up to 4 °C [116]. These temperature and humidity variations can be attributed to two main factors: differences in climatic, agronomic, and structural conditions among studies, and discrepancies in the height at which measurements were taken. Additionally, there is strong evidence of reduced water evaporation in AVS environments, making such systems particularly suitable for water-scarce areas [47,117–119].

Figure 9 highlights strategies used to optimize APV systems by varying the geometry, density, and height of PV modules while integrating additional functionalities. Beyond energy efficiency, the arrangement of panels can create pathways and spaces for human or animal activities. Although increasing the height of modules may raise costs, it enables additional features like water collection, ground stabilization, or educational uses for

local communities. These innovations can yield both ecological and economic benefits. Therefore, a three-dimensional spatial approach is ideal for sustainable and multifunctional design [26].

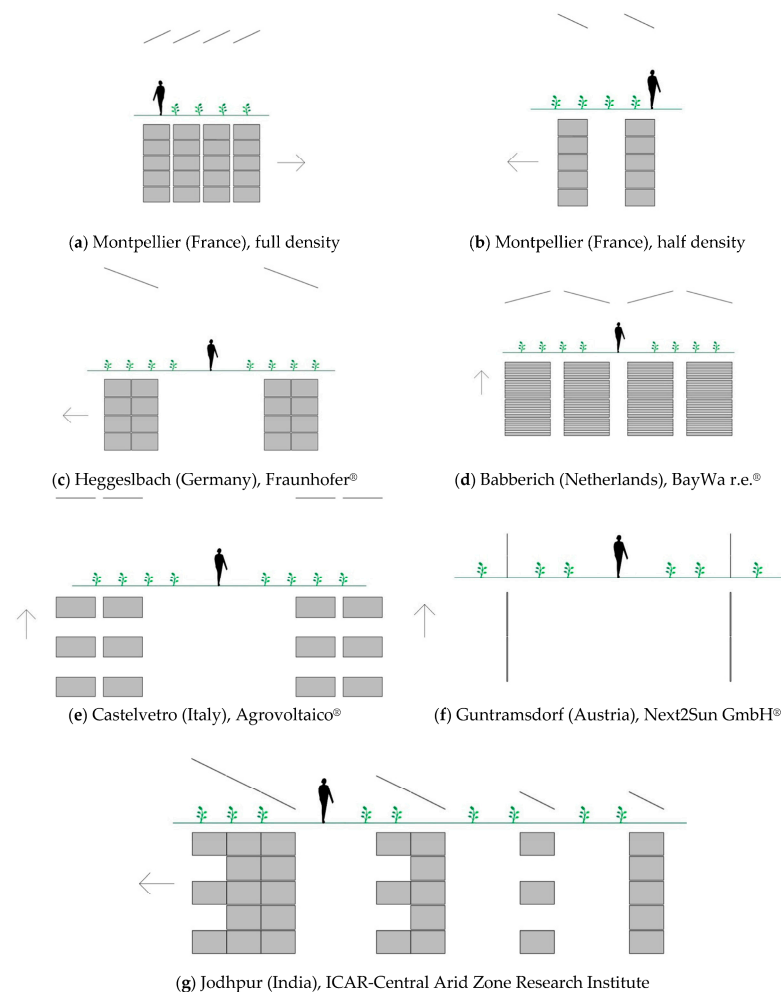


Figure 9. Various pattern solutions, either already implemented or under investigation, are applied in open-field APV systems. The arrows point to the north [26].

3.4. Socio-Economic Analysis

AVS technology is experiencing rapid growth, with the global market expected to reach USD 9.3 billion by 2031. However, its widespread adoption is dependent on a regulatory framework that varies from country to country. Some nations are more advanced than others, and there is a need to reform AVS regulations to promote energy justice and foster the sector's growth [40].

In certain regions, farmers are supportive of AVSs, but bureaucratic challenges and inadequate laws hinder the technology's adoption. This requires institutional reforms to encourage cooperation between the agricultural and energy sectors [120]. In tribal lands, AVSs have the potential to enhance the energy independence of Indigenous communities, although the prohibitive costs and socio-ecological concerns present obstacles [121]. AVSs could fulfill a huge portion of energy needs, but only with the careful management of ecologically sensitive land [122]. Solar leasing contracts also restrict the potential of AVS, preventing continued agricultural production on the same land [123].

Overall, the adoption of AVS requires a complex process that depends on legislative reforms and finding a balance between agricultural and energy interests. In urban areas, the presence of AVSs on rooftops emerges as a promising solution for sustainable cities,

alleviating land use competition. A case study in Shenzhen demonstrated that urban rooftops could meet the demand for lettuce, although this would require high water usage for irrigation [124].

While solar farms contribute to the expansion of renewable energy, they can negatively affect natural hydrological processes. AVSs can mitigate these impacts by improving water infiltration and stormwater management [125]. However, AVSs need incentives to be competitive. They are more sustainable than traditional photovoltaic systems, reducing environmental impacts by 15–55% [126]. AVSs could improve both food and energy security, but overcoming local challenges will require policies and investments [127].

Integrating conservation farming practices with AVSs could enhance resilience and reduce greenhouse gas emissions [128]. AVSs thus offers a multifunctional solution, but their success relies on balanced resource management and the necessary political and financial support. While existing regulations and funding opportunities are promising, challenges in adapting the technology to local agricultural practices and a shortage of skilled professionals remain significant hurdles [42]. With growing global competition for agricultural land, AVS installations can optimize land use by enhancing both food and energy production [129].

Research on AVSs is expanding rapidly, but there is still no standardized method for evaluating projections [130]. In regions with targeted policies and support programs, the adoption of photovoltaic agriculture is on the rise, although the costs remain an obstacle [43,131]. Finally, the use of microgrid photovoltaic systems is helping to improve food security and enhance agricultural resilience [132].

3.5. Monitoring Analysis

Remote sensing through satellite images is a powerful tool for investigating AVSs from several points of view. First, a study evaluated the benefits in terms of reducing carbon dioxide emissions over the lifetime of an AVS [133]. Promising results were obtained using satellite images, processed with deep learning techniques, to evaluate the carbon emissions of a photovoltaic system integrated with agriculture.

The second aspect to be analyzed was the impact of the photovoltaic system on plants. The impact of installing a solar system on the agricultural environment was evaluated: we found a decrease in moisture content and, as a result, a moderate decrease in vegetation indices [134]. Environmental sensors are essential for monitoring environmental parameters such as temperature, humidity, wind speed and direction, but also solar radiation and many others. These data are used to regulate the panels and to manage automatic systems such as irrigation even more efficiently [54,56]. The integration of monitoring tools with IoT systems and real-time data analysis offers a unique opportunity to further improve agronomic management. These systems enable more efficient resource management and greater overall sustainability for AVSs, making them an adaptable solution for various climatic and agricultural conditions [44,66]. The integration of IoT with decision support systems (DSSs) enhances AVSs by enabling precise monitoring, real-time adjustments, and efficient resource management. While challenges include high costs and data security, the benefits, such as optimized productivity, reduced environmental impact, and adaptability to climate variability, make IoT a transformative solution. Simulation models and computational tools such as PVsyst® and CFD (Computational Fluid Dynamics) models are employed to analyze the microclimate under the panels and optimize their layout [50,135].

PAR is crucial in AVSs because it directly affects plant photosynthesis and growth. These systems integrate solar panels with agricultural land, often creating partial shading on crops. This shading can reduce the amount of direct sunlight reaching the plants but can also increase diffuse light, which plants can utilize more efficiently for photosynthesis. A

model that separates direct from diffuse PAR using atmospheric predictors, such as optical thickness and aerosol depth, was introduced, demonstrating high accuracy in high-latitude AVS applications [136]. In contrast, another study focuses on satellite-based methods for PAR estimation, obtaining high correlations with ground measurements in different regions [137]. Both approaches advance sustainable AVSs by improving the accuracy of PAR under different climatic conditions.

Another interesting aspect is Ground Coverage Ratio (GCR) in AVSs as a predictor of crop productivity. GCR represents the proportion of land area covered by photovoltaic panels and is easily calculable for distinct designs. One study analyzed how crop yields vary with different GCRs, showing that crop productivity declines as GCR increases, with a GCR below 25% needed to maintain yields above 80% of conventional levels [138]. The author suggests using GCR as a regulatory criterion for AVS, allowing simpler and cost-effective project validation.

Drones can be useful to take aerial images of large areas. The aim is to acquire much more information about the health status of plants and to early detect diseases or nutrients deficiencies. This is made possible thanks to high-resolution and multispectral images. Considering the AVS context, drone information can integrate data derived from proximal sensors, improving the accuracy of data-based models and increasing the power of support decision systems [139].

Table 3 provides a detailed overview of the environmental parameters and technologies relevant to the analysis of agricultural and photovoltaic performance, assessing characteristics, costs, compatibility with AVSs, and required skills. Each parameter is described through specific units of measurement (U.M.) and supported by bibliographical references. The values in the cost and AVS compatibility columns are represented by ‘+’, symbols indicating the intensity of the parameter: as the number of symbols increases (e.g., +, ++, etc.), the relevance or weight of that factor increases. For example, a +++ value for the parameter IoT integration and real-time analysis indicates a high cost and strong compatibility with AVSs. The degree of expertise needed column highlights the level of technical expertise required, where ‘+’ symbols increase the need for a high level of preparation or specialist knowledge.

Table 3. Parameters and Technologies for Monitoring.

	Parameter	Description	U.M.	Cost	AVS Compatibility	Degree of Expertise Needed	Citations
Environmental Monitoring	Moisture	Ambient humidity	%	+	++	+	[134]
	Temperature	Ambient temperature	°C	++	+++	+	[54,56,134]
	Wind	Wind speed and direction	m/s; “°”	++	+++	+	[54,56,134,140]
	Solar radiation	Solar radiation on the ground	W/m ²	++	+++	+	[54,56,134]
Irrigation monitoring	Electrical Conductivity	Water salinity	dS/m	++	++	+	[141,142]
	pH	Hydrogenionic potential	n/a	+	+++	+	[141,142]
	Water temperature	Irrigation water temperature	°C	++	+++	+	[134,141]

Table 3. Cont.

	Parameter	Description	U.M.	Cost	AVS Compatibility	Degree of Expertise Needed	Citations
Soil monitoring	Nitrogen (N)	Nitrogen levels for vegetative growth	mg/L, ppm	++	++	++	[143,144]
	Phosphorus (P)	Phosphorus for root development	mg/L, ppm	++	++	++	[143,144]
	Potassium (K)	Potassium for stress resistance	mg/L, ppm	++	++	++	[143,144]
	Soil salinity	Salinity control for optimal absorption	dS/m	++	++	++	[145]
	Soil aeration	Porosity for gas exchange and roots	%	++	++	++	[146]
	Microelements	Availability of trace elements for metabolism	mg/L, ppm	++	++	++	[146]
Methods and tools for monitoring	Vegetation indices	Information on the health, density and vigor of the vegetation.	n/a	+	++	+++	[134]
	IoT integration and real-time analysis	Networks of physical devices, sensors, software and other technologies	n/a	+++	+++	+++	[44,66]
	Computational Fluid Dynamics models	Microclimate optimization with CFD models	n/a	+++	+++	+++	[50,135]
	PAR	Direct/diffuse PAR models for plants	n/a	++	++	+++	[136,137]
	GCR	Ratio of module area to land area	n/a	+	++	++	[138]
	Drones	Plant health monitoring with detailed images	n/a	++	+++	+++	[139]

4. Conclusions

AVSs represent a critical innovation for addressing global sustainability challenges, effectively combining agricultural production with renewable energy generation. The findings of this review highlight the numerous advantages of these systems, including optimal land use, reduced greenhouse gas emissions, and enhanced resilience to climate change through improved soil quality and water efficiency. The ability of photovoltaic panels to reduce soil evaporation and mitigate thermal stress has proven particularly valuable in arid and semi-arid climates.

Despite these benefits, the widespread adoption of AVSs is limited by high initial costs, technical complexities, and regulatory barriers. Continuous and integrated monitoring is

essential in order to optimize the performance of these systems, improving both agricultural yields and energy production. Tools such as IoT sensors, satellite imagery, and drones are pivotal for better resource management and informed decision-making. Additionally, the GCR has been identified as a key indicator for evaluating the impact of photovoltaic panels on agricultural yields, emphasizing the need to balance land coverage with productivity. These aspects are specific directions for future research. Additionally, regulatory, socio-economic, and human health aspects will also need to be analyzed further.

The bibliographic analysis revealed significant geographical disparities in research: while the United States and China dominate in terms of study numbers, many regions, such as Africa and parts of Asia, remain underrepresented. Furthermore, crop analysis shows a stronger focus on species like tomatoes, rice, and lettuce, while other crops and agricultural systems are still underexplored.

The success of AVSs will require greater collaboration between the agricultural and energy sectors, supported by clear policies, economic incentives, and investments in research. Regulations must be harmonized to reduce bureaucratic obstacles and promote large-scale adoption, fostering an inclusive approach that integrates agricultural, energy, and social needs. With adequate political and technological support, AVSs have the potential to become a key element of a sustainable future that can address food and energy security challenges in an integrated manner. The large-scale adoption of such systems could contribute significantly to ensuring a stable food supply, especially in the most vulnerable areas where agricultural resources and access to renewable energy sources are limited. For example, in Africa, AVSs could help bridge the gap in food and energy security. In regions where both agricultural productivity and access to renewable energy sources are limited, AVSs offer a viable solution to simultaneously improve food security and energy independence. In addition, AVSs offer the possibility to optimize land use, reduce greenhouse gas emissions, and improve efficiency in the use of natural resources, such as water and soil, by promoting more resilient agro-cultural production and complementary renewable energy generation. Targeted investments in research, the development of more efficient technologies, and the creation of policies that foster their widespread adoption will be crucial, and AVSs can become a reference point for the transition to more sustainable agricultural and energy models. The performance of AVSs is strictly dependent on the microclimate created by solar panels. However, these conditions can affect health aspects, such as air quality and the proliferation of microorganisms, with potential implications for workers' health and local communities. Monitoring the interactions between microclimate, crop growth, and environmental conditions is essential to designing sustainable AVSs that mitigate health risks and respond to global challenges.

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