PHOTOVOLTAIC TECHNOLOGIES IN AGRIVOLTAIC SYSTEMS: A GLOBAL SYSTEMATIC REVIEW (2019–2024)

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Abstract

Aiming to enhance both agricultural productivity and renewable energy generation, agrophotovoltaic (AgriPV) systems enable the coexistence of crop cultivation and photovoltaic electricity production on the same land area. These systems not only harness solar radiation but also provide beneficial shading for certain crop species. This bibliographic and technological study aims to identify the main photovoltaic technologies adopted in AgriPV systems across different regions of the world, with a particular focus on development trends and the characteristics of implemented solutions. The results of a wide range of scientific articles, academic theses, and technical documents are analyzed. Through a systematic literature review, a total of 1,135 publications published between 2019 and 2024 were retrieved from two academic databases. After applying five filtering stages, a final sample of 33 publications was obtained and analyzed using a thematic approach.

Keywords: agrivoltaic systems; photovoltaic technologies; solar energy; systematic review; dual land use

1. Introduction

Agrophotovoltaic systems (AgriPV) were characterized by Dupraz et al. (2011) as the simultaneous combination of agricultural cultivation and photovoltaic power generation on the same land area, aiming to optimize land use. These systems are emerging as an integrated solution to challenges related to land-use competition, food security, and the transition toward renewable energy sources (Trommsdorff et al., 2021a; Riaz et al., 2021a). Despite their potential, selecting the most suitable photovoltaic technologies for different agricultural contexts remains a technical and economic challenge. This selection requires a balancing energy yield with light transmission to crops (Dupraz et al. 2011). In this context, analyses tend to focus on specific technologies or localized layouts, often case studies, rather than on a systematic mapping that would enable broad comparisons across technologies and contexts.

This study addresses that gap through a systematic literature review covering 1,135 publications (2019–2024) retrieved from two academic databases and, after successive screening stages, narrowed to 33 key articles. The objective is to map the global use of different types of photovoltaic modules in AgriPV systems, synthesizing design parameters and summarizing energy and agronomic outcomes associated with each technology, in order to clarify the technology–context trade-offs that guide adoption.

Understanding which photovoltaic panel technologies are most widely used in AgriPV projects is essential for optimizing energy production and achieving better integration with agricultural activities. Accordingly, this research not only describes the current deployment of AgriPV systems worldwide but also provides insights that support the design of more efficient and sustainable strategies for panel selection and configuration in agricultural environments. The results highlight the main photovoltaic technologies identified and present a geographical mapping of the countries in which they have been implemented, contributing to the advancement of the academic and technical community working on AgriPV research and implementation.

2. Methodology

The methodology adopted in this study is structured into three main stages: (2.1) definition of the fundamental criteria for the systematic review, consolidated in a review protocol; (2.2) filtering process of the studies based on these criteria; and (2.3) presentation and analysis of the bibliometric and thematic results derived from the final selected sample.

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2.1. Review Protocol

The methodology followed the systematic review principles proposed by Tranfield et al. (2003), and comprised six methodological steps, summarized in Figure 1: formulation of research questions, selection of databases, development of search strings, definition of inclusion criteria, a multi-stage screening process, and selection of analysis methods.

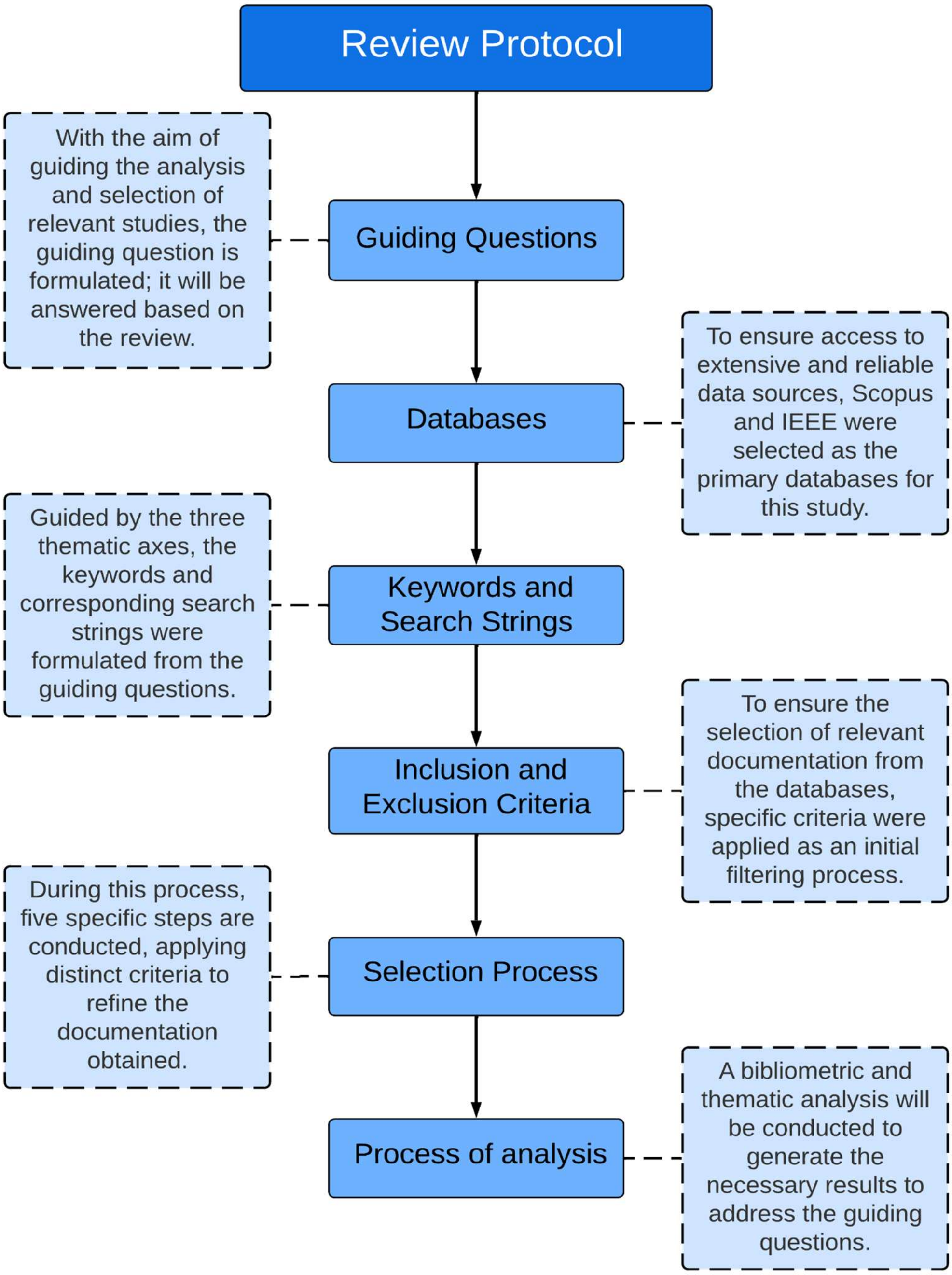


Figure 1: Review Protocol.

2.1.1 Guiding Questions

The guiding research question was defined to direct the analysis and selection of the most relevant studies, serving as a filtering tool for the articles and ensuring that the study’s objectives are met. In this research, the guiding question is: “Which photovoltaic technologies are most commonly used in AgriPV projects?”. This question represents a direct reformulation of the previously established general objective.

2.1.2 Databases

The review utilized Scopus and IEEE Xplore databases, chosen for extensive coverage in the fields of engineering, energy, and technology. Both databases provide access to quality controlled scientific publications, ensuring a rigorous, up to date, and representative literature review, thereby strengthening the validity and credibility of the study.

2.1.3 Keywords and Search Strings

To optimize document retrieval, advanced search options were used, introducing keywords relevant to the guiding research questions. These keywords were organized into three main categories: water, energy, and food, as shown in Table 1. Subsequently, keywords within each category were combined to construct search strings, which were entered into the databases to obtain relevant documents, detailed in Table 2.

Table 1: Classification of Keywords by Category.

Water	Energy	Food
irrigation	agri-PV	agriculture
photovoltaic irrigation	agrophotovoltaic	land use intensification
water management	agrivoltaic	agricultural production
drip irrigation	agri-solar	rural development
climate changes	photovoltaic systems	agricultural policies
	green technologies	
	energy policies	

Table 2: Search Strings and Corresponding Databases.

Search Strings	Databases
“agri-PV” OR “agri-solar” OR “agrophotovoltaic	Scopus and IEEE
“irrigation” AND “agrivoltaic” AND “agriculture”	Scopus and IEEE
“photovoltaic systems” AND “green technologies” AND “agriculture”	IEEE
“photovoltaic systems” AND “green technologies”	Scopus
“rural development” AND “drip irrigation”	IEEE
“agrivoltaic” AND “agriculture”	Scopus and IEEE
“water management” AND “photovoltaic”	Scopus

2.1.4 Inclusion and Exclusion Criteria

The relevance of the documentation in this study was determined by its direct relation to the guiding questions, applying criteria to identify high-quality sources. Inclusion and exclusion criteria were established to facilitate the selection of relevant and valuable documents for analysis. The criteria presented in Tables 3 and 4 were designed to ensure the quality and coherence of the information analyzed. Documents related to the three main thematic axes were included, while those not aligned were excluded, preventing deviations from the study's focus.

Table 3: Inclusion Criteria.

Criterion	Description
Relevant topic	Topics related to the three thematic axes and the guiding question.
Updated	Limited to the last 5 years to capture the most currently used practices.
Reliable source	Recognized sources were prioritized to ensure clarity and quality of information.
Published in English	Only documents published in English were included to maintain a standard and facilitate access to relevant literature.

Table 4: Exclusion Criteria.

Criterion	Description
Irrelevant topic	Documents not relevant to the thematic axes or guiding question.
Outdated	Documents with obsolete information that is no longer relevant.
Ambiguous methodology	Insufficient description of study methods, making results difficult to assess.
Duplicate studies	If the same study appeared in multiple sources, the version in Scopus was prioritized due to richer bibliometric information.

2.1.5 Selection Process

Different filters were applied to identify documents that were truly relevant and could address at least one of the guiding questions. For the systematic literature review, five steps were applied to the initial results obtained from the Scopus and IEEE search strings:

- Step 1 – Interface Filter: Filters for year (2019–2024), final version, and language (English) were applied directly in the search interfaces, as mentioned in Tables 3 and 4.
- Step 2 – Title Filter: Documents whose titles contained keywords or were related to the guiding question were selected, allowing for rapid identification of the most relevant studies and optimizing selection amid a large volume of results.
- Step 3 – Abstract Filter: The abstracts of preselected documents were reviewed to determine which directly addressed the guiding question, further refining the sample.

- Step 4 – Introduction and Results Analysis: A detailed review of the introduction and results sections was conducted to verify coherence with the three thematic axes and potential relevance to the guiding question. This ensures a more rigorous and precise selection.

- Step 5 – Full Text Review: A comprehensive review of the remaining documents was performed to confirm that they provide relevant and substantial information contributing to answering the guiding question. Only documents meeting this criterion were included in the final study, ensuring relevance and meaningful contribution.

2.2 Filtering Process

Once the initial sample was obtained, .csv files containing article metadata were downloaded to apply the filtering process described above (see Section 3.1.2). The first filter was applied directly in Scopus and IEEE Xplore, while steps 2–5were carried out in Google Sheets, organizing metadata by author, title, DOI, and link to facilitate access. At each stage, different sections of the articles were reviewed to determine whether they could contribute to answering the guiding question. Articles with potential advanced to the next step, while others were discarded. Documents that were duplicates, not written in English, or whose full text was inaccessible were also removed, following the established inclusion and exclusion criteria.

2.3 Process of analysis and synthesis of results

In the final stage of the methodology, the selected studies were analyzed through a thematic approach aimed at answering the guiding research question. The results were synthesized and organized into a table that highlights the photovoltaic technologies adopted in AgriPV systems, along with the countries and authors responsible for the studies.

3. Results and discussions

3.1. Filtering process results

During the filtering process, the initial screening applied to the databases defined in the protocol yielded 1,135 papers. Of these, 840 were excluded based on title screening, 94 during abstract analysis, 100 after reading introductions and conclusions, and 69 after full-text review. As a result, 33 articles were selected for thematic analysis. The number of excluded articles at each stage is detailed in Figure 2.

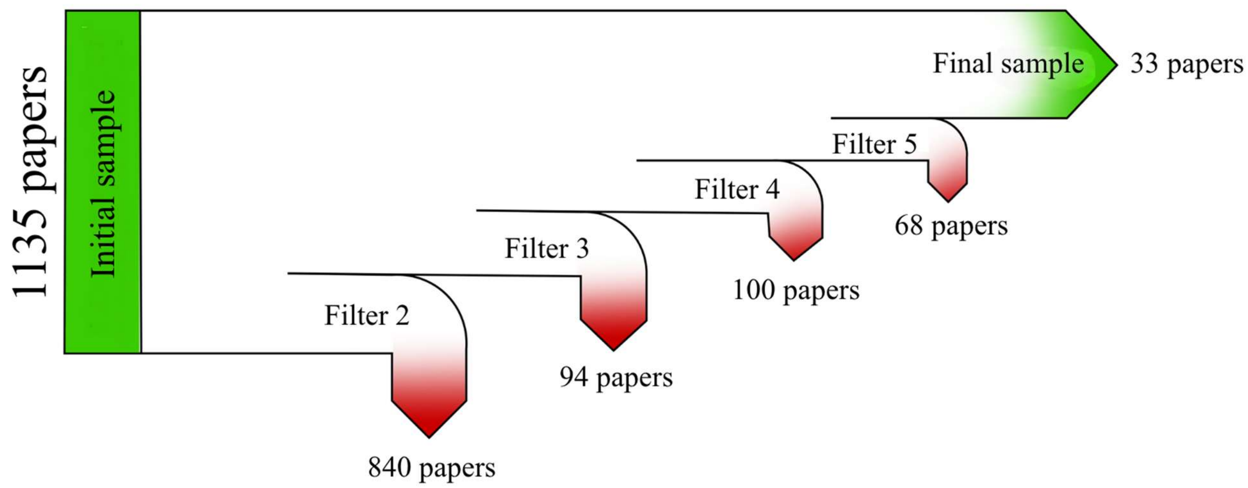
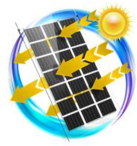
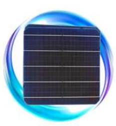
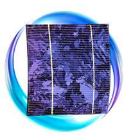


Figure 2: Step filtration process.

3.2. Main photovoltaic module technologies employed in AgriPV systems

Based on the articles in the final sample, Table 5 summarizes the different photovoltaic module technologies employed in agrivoltaics systems, indicating the corresponding studies and countries. Following the table, observations related to their application, feasibility, and reported impacts for each technology are discussed.

Table 5: Main photovoltaic module technologies employed in agrivoltaics systems.

Technologies		Sources	Country
	Monofacial	Alam et al. (2023); Cho et al. (2020); Kallioğlu et al. (2024); Kavga et al. (2023); Kim et al. (2021); Safat Dipta et al. (2022).	Australia, South Korea (2), Greece, Hungary, Pakistan.
	Bifacial	Alam et al. (2021); Arena et al. (2024); Cho et al. (2020); Ferreira et al. (2024); Gheorghiu et al. (2022); Jamil et al. (2023); Jahangir et al. (2022); Katsikogiannis et al. (2022); Kim et al. (2021); Kim et al. (2023); Reher et al. (2024); Riaz et al. (2020); Riaz et al. (2021); Trommsdorff et al. (2021).	Germany (2), Belgium, Canada, South Korea (3), United States (3), Italy, Pakistan (2), Netherlands, Portugal, Romania.
	Semitransparent	Fernández et al. (2022); Kavga et al. (2023); Lu et al. (2022); Osterthun et al. (2021); Safat Dipta et al. (2022); Thompson et al. (2020); Trommsdorff et al. (2022); Uchanski et al. (2023); Yeoh et al. (2021).	Germany (2), Australia, Spain, United States, Greece, Malaysia (2), United Kingdom.
	Thin Film	Kallioğlu et al. (2024); Trommsdorff et al. (2022); Uchanski et al. (2023).	Germany, United States, Hungary.
	Concentrators	Essahili et al. (2022); Gorjian et al. (2023); Hu et al. (2024); Trommsdorff et al. (2022); Vu et al. (2022).	Germany, China, Morocco, Sweden, Vietnam.
	Monocrystalline	Grubbs et al. (2024); Sarr et al. (2023).	Senegal, United States.
	Polycrystalline	Grubbs et al. (2024); Sarr et al. (2023).	Senegal, United States.

3.2.1 Monofacial Modules

The first technology corresponds to monofacial photovoltaic modules, characterized by their ability to capture solar energy only on one side. In the study conducted in Korea by Kim et al. (2021), different shading percentages over crops (21.3%, 25.6%, and 32%) and their influence on electrical generation were analyzed. The results indicate that higher shading levels allow for the installation of a greater number of solar modules per unit area (35, 56, and 70, respectively).

It is important to note that the works by Cho et al. (2020), Safat Dipta et al. (2022), Kallioğlu et al. (2024), Alam et al. (2023), and Kavga et al. (2023) are included for their comparative analyses involving other photovoltaic technologies.

3.2.2 Bifacial Modules

The next technology corresponds to bifacial modules, which stand out for their ability to capture irradiance from both the front and rear sides, thereby maximizing total energy utilization. According to studies conducted by Ferrera et al. (2024) and Jamil et al. (2023) in Portugal and Canada, respectively, these modules achieve superior performance when installed at greater heights, as both the available irradiance and the bifacial gain—defined as the relative increase in energy generation of a bifacial module compared to a monofacial one under identical operating conditions (Kim et al., 2021) are enhanced.

Both monofacial and bifacial modules exhibit similar patterns in power generation. However, monofacial modules demonstrate approximately 10% lower performance compared to bifacial modules per installed unit (Cho et al., 2020). This difference is associated with the bifacial gain. These findings highlight the importance of selecting the most suitable technology according to specific environmental and operational conditions (Kim et al., 2023; Riaz et al., 2021).

Another key parameter influencing bifacial systems is albedo, defined as the ratio of reflected solar radiation to the total received radiation. Light-colored surfaces, such as sandy soils or reflective coatings, exhibit high albedo, whereas dark or shaded surfaces show low values. Higher albedo enables greater reflected light to reach the rear side of the modules, thereby enhancing their energy output (Trommsdorff et al., 2021; Katsikogiannis et al., 2022). The crop architecture plays a crucial role in this regard, as vegetation can cast shadows on the ground, reducing albedo and consequently lowering module performance (Katsikogiannis et al., 2022). The study by Jahangir et al. (2022) further demonstrated that artificially increasing albedo can significantly improve overall energy generation.

Common configurations in bifacial systems include tilted and vertical layouts. The vertical arrangement, in particular, is simpler to construct and allows agricultural vehicles to pass between module rows, providing an operational advantage (Reher et al., 2024; Jamil et al., 2023; Trommsdorff et al., 2021). In northern hemisphere installations, vertically oriented bifacial modules facing east and west produce less energy throughout the day than south-oriented tilted systems. However, their economic performance is comparable to that of monofacial modules due to lower maintenance requirements and the production of a more uniform ground shadow, which benefits crop growth, as demonstrated in the study by Alam et al. (2023) conducted in Pakistan. Additionally, vertically mounted bifacial modules tend to operate at lower temperatures than tilted ones, contributing to higher efficiency (Arena et al., 2024; Riaz et al., 2020).

According to Gheorghiu et al. (2020), in a study conducted in Romania, the seasonal efficiency of bifacial systems varies significantly. A key indicator of this variability is the Performance Ratio (PR), which compares the actual energy generated with the theoretical maximum under ideal conditions. During winter, the PR of vertical systems exceeds 1.0, indicating higher-than-expected performance, while in summer, it drops below 0.8. In contrast, tilted systems maintain PR values between 0.9 and 1.0 throughout the year, demonstrating greater operational stability.

Furthermore, the annual energy yield of AgriPV systems, both monofacial and bifacial, tends to decrease as the tilt angle deviates from the optimal value. Although such variations can affect annual efficiency, tilted configurations consistently exhibit greater stability than vertical bifacial systems (Riaz et al., 2021; Gheorghiu et al., 2022).

3.2.3 Semitransparent Modules

One of the most promising innovations in the AgriPV field is the development of semitransparent photovoltaic technologies. These allow the simultaneous production of electricity and crop cultivation by permitting the passage of light useful for photosynthesis, thus reducing land-use conflicts. Semitransparent modules operate by selectively filtering certain wavelengths of the solar spectrum transmitting those necessary for plant growth while converting others into electricity (Yeoh et al., 2021; Osterthun et al., 2021).

Within this category are technologies based on crystalline silicon, organic solar cells, and dye-sensitized solar cells, each with specific characteristics in operation, efficiency, and application.

Semitransparent crystalline silicon technology stands out for its higher efficiency compared to other emerging transparent options. It offers advantages such as long-term stability and proven outdoor performance. Moreover, the transparency level can be adjusted by modifying the cell pattern, glass color, or substrate type, providing high adaptability to various crops and agricultural conditions (Fernández et al., 2022; Trommsdorff et al., 2022).

Organic solar cells have shown great potential in AgriPV systems, reaching a certified efficiency of 18.2% in 2021, as reported by Lu et al. (2022) in Malaysia. These cells are lightweight, flexible, and environmentally friendly, which facilitates their integration into agricultural structures. Although still less cost-competitive than conventional monofacial modules, continuous improvements in efficiency and lifespan are making them increasingly viable (Kavga et al., 2023; Safat Dipta et al., 2022).

Dye-sensitized solar cells, also classified as semitransparent, offer additional advantages such as lower sensitivity to temperature and light incidence angle, maintaining consistent performance under varying environmental conditions (Yeoh et al., 2021).

Semitransparent modules provide partial shading, reducing soil and air temperatures and improving the microclimate around plants by mitigating heat stress. Under moderate thermal conditions, crop rows can be placed closer together without hindering plant development. Under high solar exposure, shorter row spacing can cause heat buildup and reduced air circulation, negatively affecting growth and promoting disease. By maintaining cooler environments while allowing sufficient light for photosynthesis, semitransparent modules enable more compact crop designs. Moreover, partial shading enhances light distribution within the canopy, promoting more uniform growth. This effect is particularly beneficial in orchard-based AgriPV systems, where glass between cells can also serve as protective covering for crops (Uchanski et al., 2023; Trommsdorff et al., 2022; Thompson et al., 2020).

3.2.4 Thin-Film Modules

The next technology comprises thin-film photovoltaic modules, which exhibit more uniform transparency compared to other types of modules. This allows for a more homogeneous light distribution over crops, resulting in even plant growth and reducing excessive shadowing. These modules are also flexible in size, shape, and appearance, enabling easy integration into diverse agricultural structures (Uchanski et al., 2023; Trommsdorff et al., 2022). Although their efficiency is lower, around 18%, thin-film modules are more cost-effective and maintain good performance under high-temperature conditions due to their low temperature coefficient (Kallioğlu et al., 2024).

3.2.5 Concentrator Systems

Concentrator photovoltaic systems (CPVs) are relatively uncommon in AgriPV applications due to their dependence on high direct solar radiation and tracking mechanisms, which complicate agricultural integration. These systems employ lenses or mirrors to focus sunlight onto photovoltaic cells, allowing high-efficiency electricity generation while permitting diffuse and partial direct sunlight to reach the crops (Vu et al., 2022; Gorjian et al., 2023). CPV systems provide homogeneous and reduced shading, as well as lower wind loads and mounting structure costs (Trommsdorff et al., 2022; Vu et al., 2022).

Furthermore, this technology is versatile, as it can be integrated with other energy systems to improve overall solar resource utilization. For instance, Hu et al. (2024) proposed a hybrid system in which concentrated sunlight is strategically split to supply a solar heater, crops, and photovoltaic modules simultaneously. Recent studies have also explored luminescent solar concentrators, which use materials such as rare-earth elements known for their optical properties that enhance energy conversion by absorbing and re-emitting light efficiently. Although these technologies still require further development for large-scale AgriPV deployment, they show promising potential to improve overall energy efficiency (Essahili et al., 2022).

3.2.6 Monocrystalline and Polycrystalline

Regarding crystalline silicon technologies, monocrystalline modules dominate the global market (70% in 2019) with efficiencies reaching 27% under optimal conditions (Sarr et al., 2023). However, their opacity may hinder photosynthesis, requiring careful assessment in AgriPV contexts (Grubbs et al., 2024). Polycrystalline modules, though more affordable, offer lower efficiency and block a larger portion of photosynthetically active radiation, as demonstrated in U.S.-based studies (Grubbs et al., 2024).

4. Conclusions

Throughout the article, the most widely used technologies in AgriPV systems are presented, with bifacial and semi-transparent modules being the most commonly employed due to their energy efficiency and compatibility with agricultural practices. Monofacial modules, although more economical, are being replaced because of their lower performance, yet remain useful for initial or low-cost research applications given their reduced price. On the other hand, thin-film modules are advantageous under high-temperature environmental conditions, as they exhibit a lower temperature coefficient compared to the other analyzed technologies. Finally, concentrator-based systems represent the technology with the greatest variability in application and subtypes, being primarily investigated for specific conditions and configurations.

Overall, the selection of the most suitable technology depends on a balance between energy production, food production, and land use. Therefore, the future development of AgriPV systems should be directed toward context-specific solutions, taking into account the environmental, technological, and productive conditions of each site.

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