Agrivoltaic systems: a literature review

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ABSTRACT

Agrivoltaic systems integrate solar energy generation with agricultural production to achieve efficient land use and mitigate climate change. This study presents a bibliometric analysis of the scientific literature on this topic, published from 2013 to 2023, to identify key trends, research areas, and emerging topics. Using the preferred reporting items for systematic reviews and meta-analyses (PRISMA) methodology and data from the Scopus database, the analysis was conducted with the R package bibliometrix and VOSviewer software. The results show remarkable growth in scientific output since 2020, with the United States, China, and Germany as the leading countries. The findings reveal the benefits of agrivoltaic systems, such as increased crop productivity, water-use efficiency, and income diversification for farmers. Emerging topics include the optimization of panel configurations and socioeconomic implications. Despite these benefits, challenges like high initial costs, social acceptance, and the need for adaptable designs persist. The conclusions underscore the importance of specific policies and incentives to support the adoption of these technologies. This analysis provides a comprehensive overview of the state of agrivoltaic systems, offering valuable insights for researchers, policymakers, and other stakeholders.

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1. INTRODUCTION

The world, in order to reduce the emission of gases that accelerate global warming, is looking for alternatives for energy generation, through mitigation and adaptation strategies, among which are the transition to renewable energies and the improvement of energy efficiency [1]. The growing demand for energy for different purposes such as electricity generation, transportation, residential, commercial, and industrial heating, is being supplied by energy obtained from the burning of fossil fuels [2], which increases emissions of gases such as CO_2 and CH_4, thus accelerating the process of global warming. Within the framework of alternatives for generating electric energy that replace fossil fuels, there are photovoltaic (PV) generation systems, which, to cover large energy demands, require the deployment of solar parks that occupy large land areas. The land occupied in some regions has had an agricultural vocation, therefore, it stops being productive due to the shade under the solar panels, which directly affects what is related to the efficient use of the land [3]. This land occupation generates conflicts with other forms of land use and even problems of social acceptance of PV systems [4]. Land use efficiency has restricted the coexistence of the PV and agricultural solar power generation industries, which is why the concept of agrovoltaics has emerged, making it possible for these two industries to operate in a combined manner.

Different authors have addressed research related to agrovoltaic systems, given that it is a very new area and geographically led by the European Union with processes of implementation of agrivoltaic projects [5]. These systems offer a balanced solution for the development of agricultural and renewable energy, allowing for the sustainable "symbiosis" of food and energy on common land, and savings in the amount of water used for cultivation given that there is a reduction in evapotranspiration due to the effect of the system's panels [6]. On the other hand, deploying solar panels on crops grown in greenhouses allows for the variation of the lighting conditions required by the crop from 0% in crops that require a lot of light and up to 74% in the best of cases, with crops with low demand for solar radiation [7]. Additionally, agrovoltaic systems impact the production of some crops by improving yield, as is the case with the vertical cultivation of tender lettuce [8]. However, not all crops are suitable for solar panel conditions, therefore, one of the challenges in the implementation of agrovoltaic systems is the correct selection of the crop and the separation between panels [9]. Considering the relevance of crop selection, so that it can have an optimal yield, some authors have proposed the land equivalent ratios (LER) which is defined as the sum of the crop and electricity yield ratios in the agrovoltaic system, compared to their respective monocultures (monoculture and standard PV plant), that is, compared to having the crop and the PV generation system separated [10]. Other authors have explored the price–performance ratio (PPR). This indicator compares the additional cost of implementing an agrovoltaic system (compared to a standard PV plant) with the economic benefit of maintaining agricultural activity under such a system, concluding that agrovoltaic implementation is more economically viable (low PPR value) when combined with high-value permanent crops, such as berries, fruits or wine grapes. These crops usually have higher production prices, which improves the economic return per area. In addition, the agrovoltaic structure can replace other crop protection systems, such as hail protection nets, reducing CAPEX [11].

In order to explore the productivity of scientific articles on agrivoltaic systems and detect emerging trends related to this topic, this article presents a bibliometric analysis and a literature review. This was done from a bibliometric analysis of the last 10 years, and it is expected that the results can generate an overview for researchers on agrivoltaic systems and people who wish to deploy this type of systems.

2. METHOD

2.1. Review structure

Bibliometric analysis has been used to understand research trends in electricity generation systems, unconventional renewable energies, and even user behavior [12]-[14]. This article analyzes annual production trends by establishing the production tipping point, analyzes production by country, defining the most productive country, and identifies emerging research topics through a co-occurrence analysis of keywords. To carry out the bibliometric process in this article, the preferred reporting items for systematic reviews and meta-analyses (PRISMA) methodology was applied [15], and the analysis of the collected articles was performed using R Studio software and its bibliometrix package [16], [17] and VOSviewer [18], [19].

2.2. Data collection

The database consulted was Scopus, within a time window from 2013 to 2023, and limited to records in English. Figure 1 (see in Appendix) illustrates the methodology applied to obtain the records for the analysis, which finally totaled 132. The exclusion criterion applied was that the records were not related to the topic of agrovoltaic systems.

3. RESULTS AND DISCUSSION

Figure 2 shows the trend in article productivity and the cumulative percentage. After 2019, a significant increase in productivity was observed, rising from 10% in 2019 to 33% in 2021. This is consistent with the growth of PV generation systems reported by [20] in the 2024 global electricity report, and also with the entry into force of the Paris Agreement in 2016. The leading countries in production are the USA (105 publications) in North America, China (61 publications) in Asia, Germany (58 publications) in Europe, Algeria (3 publications) in Africa, Costa Rica (2 publications) in Central America, and Colombia (3 publications) in South America, as shown in Figure 3. The geographic distribution of the largest productions, highlighting the countries leading productivity by continent, reveals how the energy transition processes are advancing worldwide. Additionally, the geographic distribution is led by one of the seven largest economies in the world, the USA, a member of the G7, followed by one of the major emerging economies, China, a member of the BRICS, countries that, through their organizations, can contribute significantly to renewable energy issues [21].

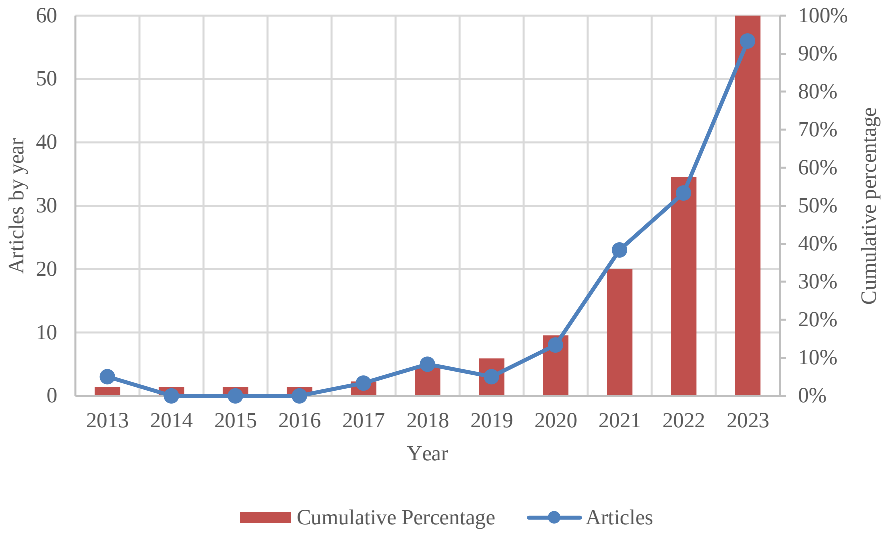

Figure 2. Publication progression and cumulative percentage

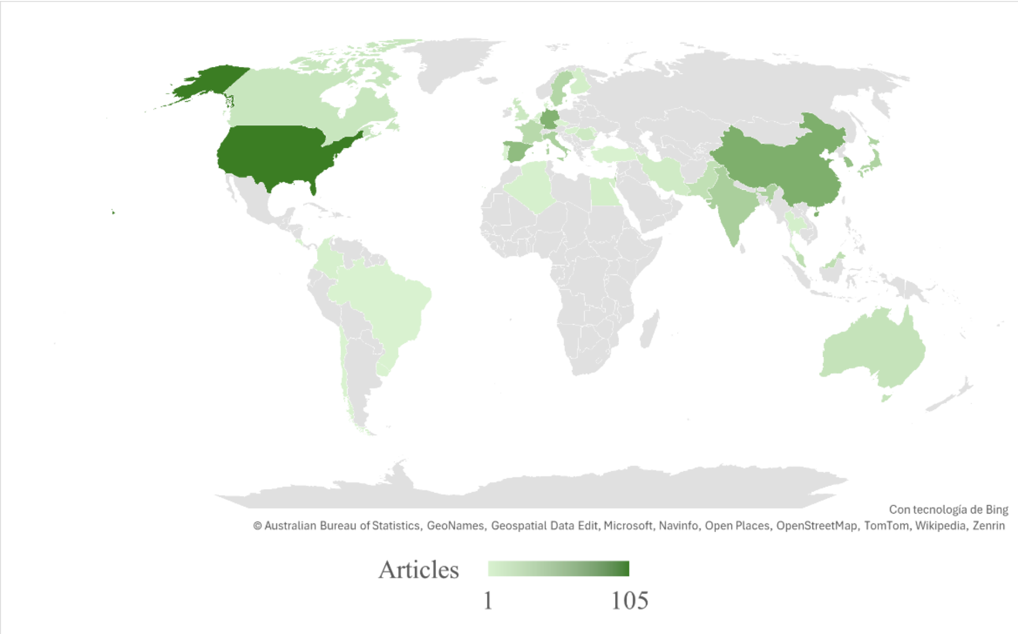

Figure 3. Global productivity distribution

Regarding author keywords that allow to show trends in emerging topics or relationships between research themes, of 271 words, 22 exceeded the minimum threshold of 3 occurrences, grouped into 6 clusters composed of 4-8 words (Figure 4). Analyzing the relationship of the first cluster (red) with the others, strong relationships are observed with a second cluster (green) through the words "agrivoltaic" and "crop", indicating that agrivoltaic systems are being studied to coexist with crops; with a third cluster (blue) thanks to the contribution that agrivoltaic systems can make to climate change through the use of solar energy; with a fourth cluster (yellow) that brings together agricultural systems; with a fifth cluster (purple) where agrivoltaic systems are studied from the effects of their shade on crops; and finally a sixth cluster (aquamarine blue) related to the need to achieve systems that positively impact the economy, society, and environment, that is, that are framed within sustainability.

Table 1 presents the 10 most cited articles since their publication. With 371 citations [22], they indicate that agrivoltaic systems can benefit crops, such as generating shade from solar panels over crops in drylands, improving water use efficiency by reducing soil evaporation and creating a more favorable microclimate for crops, increasing agricultural productivity under water scarcity conditions. Additionally, the generated solar energy provides an additional source of income for farmers, diversifying the local economy. The results show that integrating agrivoltaic systems into drylands not only optimizes the use of scarce resources like water and land but also contributes to energy and food sustainability in these regions.

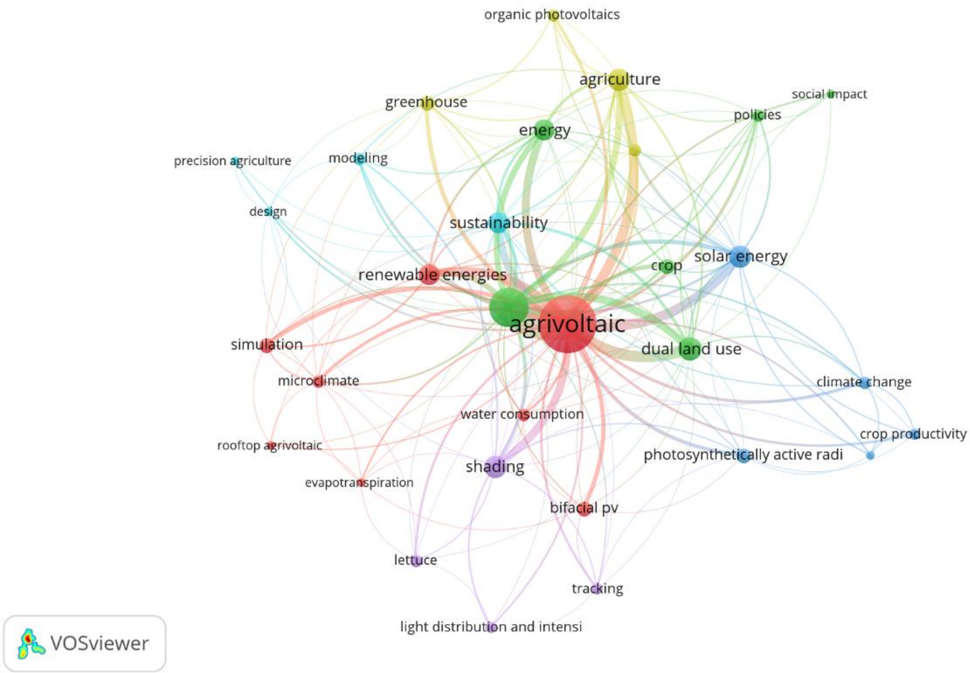

Figure 4. Author keyword co-occurrence

Table 1. Most relevant articles

Title	Year	Journal	DOI	Total citations
Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands [22]	2019	Nature sustainability	10.1038/s41893-019-0364-5	371
Agrivoltaic systems to optimise land use for electric energy production [23]	2018	Applied energy	10.1016/j.apenergy.2018.03.081	258
Microclimate under agrivoltaic systems: Is crop growth rate affected in the partial shade of solar panels? [24]	2013	Agricultural and forest meteorology	10.1016/j.agrformet.2013.04.012	244
Productivity and radiation use efficiency of lettuces grown in the partial shade of PV panels [25]	2013	European journal of agronomy	10.1016/j.eja.2012.08.003	238
Implementation of agrophotovoltaics: Techno-economic analysis of the price-performance ratio and its policy implications [11]	2020	Applied energy	10.1016/j.apenergy.2020.114737	177
Solar PV power potential is greatest over croplands [26]	2019	Scientific reports	10.1038/s41598-019-47803-3	176
Increasing the total productivity of a land by combining mobile PV panels and food crops [27]	2017	Applied energy	10.1016/j.apenergy.2017.09.113	160
Solar sharing for both food and clean energy production: performance of agrivoltaic systems for corn, a typical shade-intolerant crop [28]	2019	Environments	10.3390/environments6060065	149
How does a shelter of solar panels influence water flows in a soil–crop system? [29]	2013	European journal of agronomy	10.1016/j.eja.2013.05.004	147
Integrating solar energy with agriculture: Industry perspectives on the market, community, and socio-political dimensions of agrivoltaics [30]	2021	Energy research and social science	10.1016/j.erss.2021.102023	126

With 258 citations [23], it is indicated that agrivoltaic systems allow for dual land use, maximizing energy production without sacrificing agricultural productivity. Additionally, solar panels provide partial shade for crops, improving the microclimate, reducing water stress, and increasing water use efficiency. Furthermore, the income generated from the sale of solar energy can supplement agricultural income, diversifying economic sources for farmers.

With 244 citations, Marrou *et al.* [24] investigated the effect of solar panel shade on the growth of lettuce, cucumber, and wheat crops. Results showed that, although air temperatures and humidity were similar under shade and full sun conditions, soil temperatures were significantly lower under solar panels. Despite the reduction in light, the growth rate of the crops did not show significant differences between shaded and unshaded treatments. The authors conclude that the implementation of agrivoltaic systems can be viable without negatively affecting crop yields, suggesting a sustainable approach to land use. Additionally, the importance of light capture as a key factor in biomass accumulation is highlighted.

With 238 citations, Marrou *et al.* [25] also present results on the analysis of the impact of solar panel shade on the growth and yield of a lettuce crop (*Lactuca sativa L.*). The authors analyzed different shade levels (50% and 70%) and measured variables such as biomass accumulation and radiation interception efficiency. Results showed that lettuces grown under shade achieved comparable or higher yields than those grown in full light, and moreover, radiation interception efficiency increased under shade conditions, suggesting that agrivoltaic systems can be a viable solution to optimize land use, combining food and energy production.

With 177 citations, Schindele *et al.* [11] present the results of an analysis of the cost-benefit ratio of agrivoltaic systems, in which they indicate that while initial installation costs are high, long-term benefits in terms of land use efficiency and dual product generation (energy and food) can offset the investment. Additionally, these systems improve crop resilience to adverse weather conditions and diversify income sources for farmers. The results suggest that support policies, such as subsidies and favorable regulatory frameworks, are crucial to making agrivoltaic systems viable and accelerating their adoption.

With 176 citations, Adeh *et al.* [26] using a model that incorporates microclimatic variables such as solar radiation, air temperature, wind speed, and relative humidity, analyzed the potential of solar PV energy in different land use types. The authors found that solar panel efficiency decreases with increasing temperature and increases with light winds. Globally, crops, grasslands, and wetlands showed the highest potential for solar energy production. The research suggests that the use of agrivoltaic systems can mitigate competition for land use, allowing the coexistence of food and energy production. According to the authors, converting less than 1% of agricultural land into agrivoltaic systems could meet global energy demand.

With 160 citations, Valle *et al.* [27] analyzed how the combination of mobile PV panels with crops can increase overall land productivity. The authors implemented a system that allows harnessing solar energy for electricity generation while simultaneously using the land for agriculture, optimizing both uses without significantly compromising the yield of either. The mobile PV panels are adjusted to optimize solar energy capture during the day and also to provide partial shade to crops, which can improve the microclimate and increase crop yields under certain conditions. The results show that by combining these two uses on the same land, it is possible to achieve greater resource use efficiency, product diversification, and an increase in total production, both of energy and food. Additionally, it is highlighted that this approach can be a viable strategy to maximize productivity in areas with space constraints.

With 149 citations, Sekiyama and Nagashima [28] studied the effectiveness of agrivoltaic systems in a corn crop, comparing three configurations: no solar panels (control), low panel density, and high panel density. The results showed that corn grown under the low panel density configuration had a higher yield than the control, with a 4.9% increase in biomass and a 5.6% increase in corn yield per square meter.

With 147 citations, Marrou *et al.* [29] investigated how solar panels in an agrivoltaic system can influence water fluxes within a soil-crop system. The authors found that solar panels can alter the distribution and water balance in the soil, affecting the amount of water reaching the crops. Specifically, the panels reduce direct soil evaporation and modify plant transpiration by creating shade zones. These changes can lead to more efficient water use in some conditions, although they can also cause water stress in crops if water distribution is not managed properly. The results indicate that, while the installation of solar panels over crops can offer benefits in terms of water savings, it is crucial to consider the design and management of the system to avoid negative impacts on soil health and agricultural yield.

Finally, with 126 citations, Pascaris *et al.* [30] conducted an analysis of agrivoltaic systems from a social acceptance perspective, analyzing the perceptions of 14 solar industry professionals. The findings were organized into three dimensions: market, community, and socio-political acceptance, highlighting that public perception is crucial for the success of these projects. They were able to identify opportunities and barriers, such as the complexity of development and the need for both economic and non-monetary benefits. The authors suggest that social acceptance of these systems can be increased if projects are aligned with community priorities and generate local benefits.

4. CONCLUSION

The rise in PV systems and the various global policies and initiatives aimed at mitigating climate change have spurred research on agrivoltaic systems, as evidenced by the increase in productivity since 2019. Countries with strong economies are leading this academic productivity, as their industrial economies require a faster energy transition. This is consistent with authors who have indicated the need to strengthen public policies and economic incentives to achieve a wider deployment of agrivoltaic systems.

The most relevant articles have highlighted that agrivoltaic systems optimize land use, can improve water use efficiency for crops thanks to the shade generated by solar panels, and can even increase the productivity of some crops under shade. These impacts directly contribute to climate change mitigation and food security. Additionally, agrivoltaic systems allow farmers to diversify their income, but this must go hand in hand with benefits that are reflected in the communities.

Despite the benefits, the implementation of agrovoltaic systems faces challenges related to social acceptance, initial costs and the need for optimal designs to maximize benefits. The results obtained in this study are expected to be useful for government entities to encourage the implementation of agrovoltaic systems through subsidies, tax benefits and clear regulatory frameworks that facilitate their adoption; which would also allow promoting research in this area to consider different crops and panel configurations that could be optimal and thus achieve a productive and economic balance between agricultural production and the generation of electric energy.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Mariajosé Durán-Cabezas		✓		✓	✓	✓			✓					
Catalina Gómez-Gaviria		✓		✓	✓	✓			✓					
Vladimir Henao-Céspedes	✓	✓	✓	✓		✓	✓	✓		✓	✓	✓	✓	✓

C : **C**onceptualization	I : **I**nvestigation	Vi : **Vi**sualization
M : **M**ethodology	R : **R**esources	Su : **Su**pervision
So : **So**ftware	D : **D**ata Curation	P : **P**roject administration
Va : **Va**lidation	O : Writing - **O**riginal Draft	Fu : **Fu**nding acquisition
Fo : **Fo**rmal analysis	E : Writing - Review & **E**diting	

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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APPENDIX

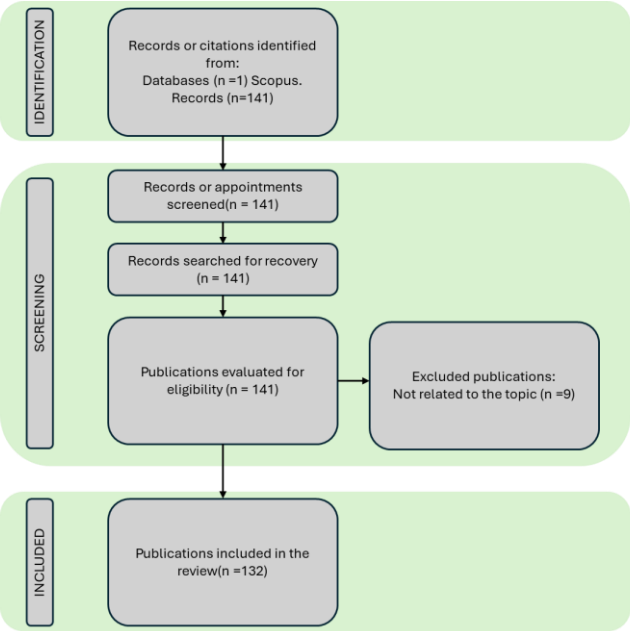

Figure 1. PRISMA applied methodology

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