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Review article

A comprehensive review of two decades of research on agrivoltaics, a promising new method for electricity and food production

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A R T I C L E I N F O

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A B S T R A C T

An agrivoltaic system combines energy production and agricultural crops in one location, addressing the growing demand for sustainable and cost-effective energy sources. The objectives of this bibliometric analysis are to identify knowledge gaps, emphasize important contributions, and highlight trends in agrivoltaic research. It is expected to support creative research in agriculture and sustainable energy, foster collaborations, and inform decision-making. This study thus employed the systematic, bibliometric and content analysis review approach to analyse research works published on the topic during the last two decades. Data from the Scopus database was used for the qualitative and quantitative analysis using the Biblioshiny package in R and VOSviewer software. The study analysed 155 documents, revealing an 18.21% annual growth in research on agrivoltaics. The most frequently used keyword was agrivoltaics, highlighting its potential for sustainability and sustainable land use. Research on the topic is found to be evolving from small-scale irrigation power generation to large-scale electricity generation, emphasizing dual land use for energy and food production. North Carolina State University and Chinese institutions are leading in agrivoltaics research. The study concluded with some identified research gaps that should be examined going into the future.

Introduction

The world's demand for energy has grown exponentially, a trend directly related to population growth. Renewable energy production has not been immune to criticism, whether it be political or local, even though it is closely aligned with sustainable development [1,2]. But the pressure to decarbonize by moving to clean, renewable energy sources like solar power has increased due to the ongoing depletion of fossil fuel resources as well as the negative effects of burning them for energy, like climate change [3–5]. Over the last few decades, solar photovoltaic (PV) technology has undergone constant technical advancements [6], opening up new avenues for producing clean, sustainable solar energy, whiles lowering costs [7]. In addition to being essential for any economy centred on agriculture, land is also necessary for the maintenance of vital ecosystem functions like biodiversity, CO_2 capture, and water cycle control [8]. The production of food and the generation of electricity in relation to land use could potentially clash due to the aggressive expansion of photovoltaics [9,10]. Increased power development makes resource competition more intense, particularly in the agricultural sector, which presently uses 12 % (1.6 billion ha) of all arable land worldwide [10]. The United Nations (UN) [11] reports that the world population is growing at a rate of 1.15 % annually, which means that food production must increase by 70 % between 2005 and 2050 to feed the projected 9.1 billion people. This is contributing to the growing conflict [12]. PV systems appear to offer tremendous promise for meeting future energy demands. However, a significant amount of land i.e., 2.0 ha per MW—is needed for its implementation [13].

Due to their potential in the food-energy nexus, agrivoltaic systems (AVS) have been the subject of a lot of research lately. Creative conceptual designs for covering open fields through demonstrative projects utilizing PV modules have yielded promising results in terms of optimizing light accessibility, reducing the need for irrigation, and offering

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protection against extreme weather events [14]. Because of its reliability in variable-scale applications, AVS technology is becoming more and more popular. This technology has enormous potential, as evidenced by the growth of research and commercial facilities worldwide [15]. Although agrivoltaics is thought to be multifunctional, monofunctional solar power plants are frequently criticized for putting food production in competition with other land uses [16]. Over the past few years, the installed capacity of agrivoltaics has grown exponentially worldwide, from 5 MW in 2012 to 2800 MW in 2020 [17]. Research done between 1982 and 2022 indicates that the installation of PV modules with agricultural plans was the main focus of PV panel land use. Land can be valued by planning and putting in PV panels so that plants can get enough sunlight. However, the installation of PV modules to generate only electricity is insufficient for plants or crops cultivation due to the land beneath the PV panels [18,19].

Different studies have reviewed different aspects of AVS in recent times. For instance, Dinesh et al. [20] reviewed agrivoltaics research, both experimental and theoretical, and examined how solar radiation affects solar power output and potential crop yields. Abidin et al. [21] reviewed in detail the key elements influencing the choices made about agronomic management and energy management (solar PV architecture) in AV systems. In another study, Klokov et al. [22] reviewed the key ideas and innovations being used to use AV to intensify agriculture. They reviewed the potential for AV to be more deeply incorporated into agricultural activities, which could also aid in the resolution of pertinent legal disputes (considered as neither rather than both components), in contrast to the mainstream discourse on the topic. Weselek et al. [23] reviewed the AVS, the study provided a succinct overview of the state of the art at the moment and future directions for agrophotovoltaic (APV) system applications. Furthermore, they talked about how APV affects crop productivity by changing the microclimate. Furthermore, [24] examined and synthesized the state-of-the-art agronomic knowledge regarding agrivoltaics and its potential for future development. Also, [25] examined layout optimization techniques and agrivoltaic engineering in the conversion to renewable energy technologies. The impact of varying panel height, spacing and density on the shading beneath the panels was also taken into account when reviewing AV farm layouts. Similarly, [26] reviewed research on AVS in Indian solar plants, the environmental, social, and microclimatic effects of solar parks, and the laws and regulations that are currently in place that support land use. Ghosh [27] examined the APV system, noting the need for more accurate forecasting instruments and resolving the disparity in stakeholder knowledge. It recommended that in order to boost APV's growth and meet Sustainable Development Goals targets, policymakers and economists work together. Sarr et al. [28] also reviewed agrivoltaics, emphasizing panel configurations, optimization technologies, and factors influencing agricultural and energy production. Similarly, research on AV, module technologies and PV array designs were reviewed by [29]. Additionally, a *meta*-analysis of performance of crops under various shading conditions was presented, along with a comparison of the agronomic potential of different crops for agricultural visualization. Finally, Lu et al. [30] reviewed the most important research conducted between 2010 and 2020 regarding the various PV materials employed in the roofing of greenhouse in different countries. The research on the organic photovoltaic as a material for greenhouse roof shading was also highlighted in the paper.

Based on the literature presented supra, several papers have covered different aspects of AVS over the years using the traditional review approach. Very little is known about the trend, evolution, and research directions on the topic going into the future. Bibliometrics is a method used to analyse written production as the primary communication channel between scholars, supporting the historical and contemporary representation of a field of study or subject. Using statistical techniques, this method enables more objective and reliable analyses, by analysing substantial amounts of documentation related to the field [31,32]. Additionally, the knowledge gained from a bibliometric review makes a significant contribution to building a solid knowledge base, encouraging interdisciplinary cooperation, and advancing the scientific community's overall progress in a particular field of study. Very few studies [22,33,34] have conducted mini reviews on the agrivoltaics research using the bibliometric approach, but fell short of detailed content analysis and potential future research directions. The objectives of this bibliometric analysis are to identify knowledge gaps, emphasize important contributions, and highlight trends in agrivoltaic research. It will support creative research in agriculture and sustainable energy, foster collaborations, and inform decision-making. As a result, this paper includes important details regarding new avenues for agrivoltaics research between 2003 and 2023. It also identifies areas that might make for intriguing future research subjects. Knowledge maps covering a wide range of subjects, literature, countries, and keywords were also generated by this investigation. To further assist researchers in understanding the state of the field and identifying hotspots, a graphical assessment of the development trends, factorial analysis, publication status, and hotspots in this field was conducted. To the best of the author's knowledge, this is the first study on agrivoltaics that combines the systematic, content analysis, and bibliometric review approaches to provide a holistic overview of the subject matter within the study period. Thus, in comparison to previously published reviews, this study's methodology and content are different and detailed.

The paper is organized as follows: the materials and method used for the study is presented in section 2. Section 3 presents the results and discussion, whiles the conclusion and future research directions are presented in section 4.

Materials and methods

There are several types of literature review techniques, including qualitative and quantitative approaches. Examples include bibliometric analyses, content analyses, *meta*-analyses, and systematic literature reviews. This study employs content analysis and bibliometric analysis techniques to investigate research questions. Content analysis helps identify "hot spots" and "blind spots" in literature, summarizing trends, and providing a deeper understanding of reviewed articles. This method, when combined with other bibliometric methods, it identifies potential directions for future study [35]. A comprehensive literature review was conducted in conjunction with a bibliometric analysis to facilitate the effective identification of scientific output related to agrivoltaics systems. When combined, these two approaches can show how scientific research has evolved in two ways: quantitatively, through the use of bibliometrics, and qualitatively, through in-depth studies of contents and topics through systematic review [36–38]. Scientific research that assembles pertinent studies on a particular topic and offers unbiased summaries of the results is known as a systematic review. It can also mean identifying and choosing findings, extracting data, and analysing outcomes seen in the scientific community. According to [39], this is particularly helpful in fields of research where there is a large volume of publications, each presenting a distinct perspective. The PRISMA protocol was followed in this paper's review to achieve the primary goals of data extraction, summaries, eligible published papers, and literature search [40]. The flow diagram for the PRISMA approach is shown in Fig. 1. The source of data for this study is the Scopus database. The Scopus database was utilized due to its reliable coverage of over 20,000 journals from reputable publishers, strict indexing requirements, extensive content, and features for visual mapping and citation analysis [32,41,42].

VOSviewer can be used to visualize other kinds of data, including similarity to an author or journal, using co-occurrence data, keywords, or co-referenced data. Essentially, VOSviewer works by building a similarity matrix and using correlation strength to determine how similar two items are to each other in the co-occurrence data. **Eq. (1)** provides the formula for determining the correlation strength.

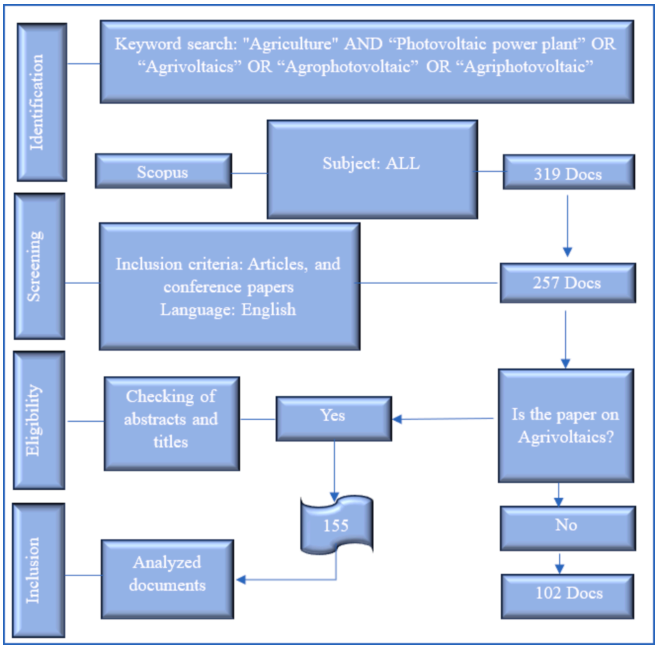


Fig.1. Flowchart for the PRISMA approach.

$$S_{ij} = C_{ij} / \omega_i \omega_j \tag{1}$$

where S_{ij} indicates how similar elements i and j are to one another, and ω_i and ω_j indicate how many times each element has been found overall, respectively.

Reducing each pair of items' weighted sum of squares representing the Euclidean distance is the aim of the plotting principle. The summation computation gives square distance more weight when there is a higher degree of similarity between the items. The expectation minimization objective function is represented by **Eq.** (2), and the bounds it adheres to are shown by **Eq.** (3). For a thorough explanation of VOSviewer, see [43].

$$V(x_1, x_2, \cdots x_n) = \sum_{i<j} S_{ij} \| \|x_i - x_j\| \|^2 \tag{2}$$

$$[2/n(n-1)] \sum_{i<j} \|x_i - x_j\| = 1 \tag{3}$$

where the vector x_i represents item i's location in the two-dimensional knowledge graph and $\| \bullet \|$ denotes the Euclidean norm. The fractional counting method was used to look for co-occurrences of the author's keywords.

VOSviewer is unique among knowledge graph viewers in that it can show the density map of the knowledge graph. Using **Eqs** (4) and (5), the density map $D(x)$ for node $x = (x_1, x_2)$ is computed.

$$D(x) = \sum_{i=1}^{n} w_i K \frac{\|x - x_i\|}{\overline{d} h} \tag{4}$$

$$\overline{d} = \frac{2}{n(n-1)} \sum_{i<j} \|x_i - x_j\| \tag{5}$$

where the kernel function is represented by $K : [0, \infty) \rightarrow [0, \infty)$; the non-increasing kernel function is represented by the Gaussian function $K(t) = exp(-t^2)$; the average distance between the nodes is denoted by $\overline{d}$, and the kernel's width is represented by h.

Results and discussion

The statistical and keyword analysis of the studied documents are analysed and presented in this section. The analysis encompasses 155 documents in total. Analysed data shows that research on the subject increased by 18.21 % per year. Ten documents had a single author, out of the 639 authors that conducted research on the topic. With an average of 17.51 citations per document, the examined documents had an average age of 3.99. The nation with the highest frequency of scientific production is China (n = 113), followed by the USA (n = 96) and India (n = 75).

Analysis of keywords and clusters

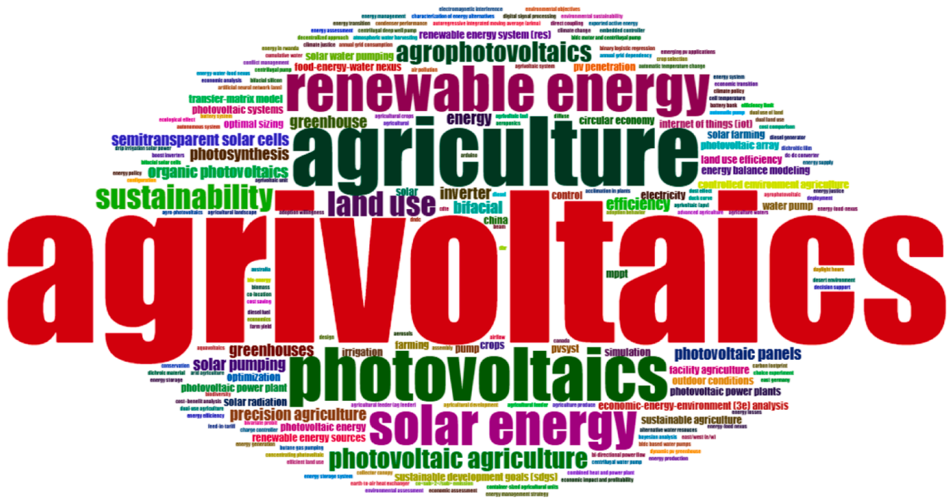
Word frequency is visually represented by word clouds. In the image representation, the frequency with which a word appears in the material under analysis dictates the size of the text. Utilizing word clouds, one can locate a written text's focus. A word cloud used in bibliometric studies to assess the most common words suggests that most research is focused in those areas. Words in smaller letters also suggest possible directions for further research. Word clouds use colour and size to transform texts into tags, or words whose relative value is visible in the final cloud [44,45]. In the word cloud presented in Fig. 2**a**, keywords such as agriculture, photovoltaics, agrivoltaics, solar energy, agrophotovoltaics, renewable energy, sustainability, photovoltaic agriculture, and land use are the prominent keywords of study. According to the data presented in Fig. 2**a,** the most frequently used author keyword is agrivoltaics which occurred 37 times within the study period.

Fig. 2**b** shows the network visualization of all keywords used in the study. According to the findings, the total number of clusters using the fractional counting method in the VOSviewer software is 5 with a total link strength of 522.50. It had a total of 1604 links. The details of the various clusters are as follows:

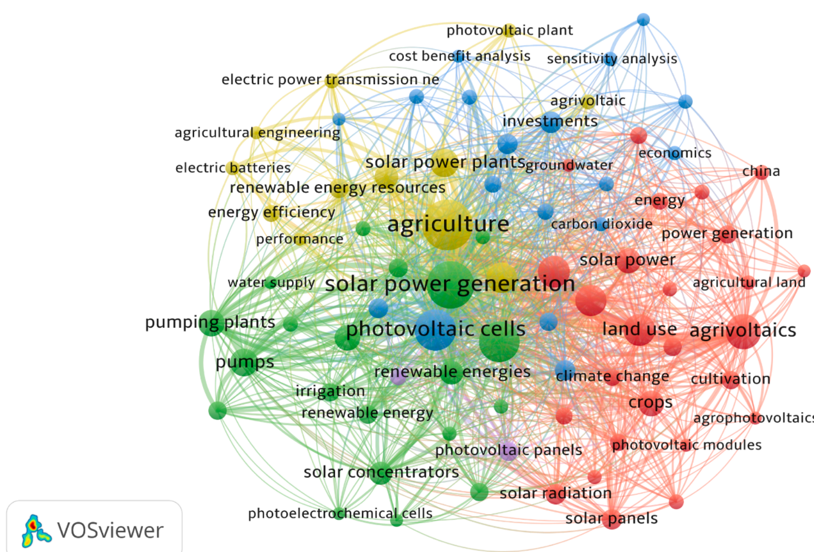
Cluster 1 (cluster red): this is the largest cluster, it has themes such as agricultural land, agricultural productions, agrivoltaics, agrophotovoltaics, alternative energy, China, climate change, crops, cultivation, electricity generation, energy, energy productions, groundwater, land use, photovoltaic modules, photovoltaic systems, photovoltaics, population statistics, power plant, solar cells, solar panels, solar power, solar radiation, sustainability, and sustainable development. The themes in this cluster examined how the concept of land use could be used to address both mitigation and adaptation strategies by allowing photovoltaics to grow without sacrificing agricultural land and by using PV modules to shade agricultural crops.

Cluster 2 (cluster green): themes such as electric power generation, electricity production, energy policy, fossil fuels, irrigation, optimization, performance assessment, photoelectrochemical cells, pumping plants, pumps, renewable energies, rural areas, renewable energy, solar cell arrays, solar concentrators, solar energy, solar photovoltaics, soar power generation, water pumping systems, and water supply appear in this cluster. Studies in this cluster looked at various technologies (i.e., PV and solar concentrators) for the generation of energy for irrigation activities in various agricultural areas [46–48].

Cluster 3 (cluster blue): in this cluster themes such as carbon dioxide, cost benefit analysis, costs, economic analysis, economic and social effects, economics, energy utilization, environmental impact, greenhouse gases, greenhouse, investments, photovoltaic agriculture, photovoltaic cells, photovoltaic effects, photovoltaic power generation, photovoltaic systems, sensitivity analysis, and solar photovoltaic systems are the items in this cluster. This cluster can be summarized into two main research focus, i.e., the assessment of the economics, and the environmental impact of the agrivoltaics to society. A primary drawback of agrivoltaic systems is their expensive infrastructure and installation costs. Compared to traditional PV systems, agrivoltaic systems are more expensive to install and maintain, but they may bring in more money from crop sales. An agrivoltaic system will require more money to install



(a)



(b)

Fig.2. (a) Word cloud for author keywords (200 words) (b) Network visualization (all keywords).

since it will need more space for plant cultivation, pumping, irrigation, harvesting, and ongoing maintenance, all of which raise operating expenses. The return on investment is contingent upon the cost of energy in the area, government grants and incentives, tax credits, and the particulars of each project [49]. For instance, the economics of an APV system at Kaposvár in Hungary was conducted by [50]. There were two comparisons done: one between APV and apple plantations, and the other between APV and PV systems. According to their study, due to the long return period of the excess investment cost, the baseline scenario demonstrated that APV systems are not competitive with PV systems in the current technological and economic environment. Moreover, farmers found APV systems less appealing. Kim et al. [51] investigated how the general public views APV power plants and the agricultural landscape, as well as how these plants affect the agricultural landscape's amenity value. The study found that rural tourism accommodation with an "agricultural landscape view" is more expensive than a "agrophotovoltaics panel view," indicating that solar panel installation on farmland reduces the value of the agricultural landscape. If solar panels are installed across Korea's farmlands, the agricultural landscape's amenity value is predicted to decline by USD 1.70 billion, or 55.0 % of the total estimated amenity value.

Cluster 4 (cluster yellow): the following are the themes that make up this cluster: agricultural engineering, agricultural robots, agriculture, agrivoltaics, electric batteries, electric power transmission, energy efficiency, performance, photovoltaic, photovoltaic plant, renewable energy resources, and solar power plant. The research direction of this cluster is mainly on assessing different technical strategies to enhance the performance of agrivoltaics systems. For instance, [52] provided a more straightforward, comprehensive, and verified model for the diffuse solar fraction; additionally, it shed light on how a panel interacts with its neighbours and how many PV panels are required to achieve an asymptotic value through shadowing. Normalizing the problem allowed for the plotting of beam and diffuse solar fractions, which are the foundation for basic tools for first-order estimates in design. Padole et al. [53] examined a case study of a 2 MW PV linked to an Indian agricultural feeder. Utilizing field measurement data, performance analysis was performed. Important variables were computed for analysis, including the capacity utilization factor (CUF) and PV penetration. The PV at Manjarda's CUF was estimated to be between 10 % and 20 %. In another study by [54], the authors evaluated the latest developments in concentrating agrivoltaics as well as the operation of CPV modules taking agricultural applications into consideration. Solar cells that were shaded were addressed using two different techniques: first, sunlight was directed onto the cells using Fresnel lenses or transparent sun-tracking louvers; secondly, near-infrared radiation was reflected onto the cells and photosynthetically active radiation was transmitted using parabolic glasses coated in a multilayer dichroic polymer film.

Cluster 5 (cluster violet): two items appeared in this cluster, i.e., photovoltaic panels and photovoltaic power plants, these two themes form the basis for the generation of energy at the various agricultural farms.

Review of the top 46 globally most cited documents on the topic

The most frequently cited papers on the subject are briefly reviewed in this section, along with an outline of the key conclusions and, if available, recommendations from those studies. The study of Dupraz et al. [55] indicated that maximizing land usage could be achieved by growing food crops and solar panels on the same piece of land. The term "agrivoltaic system" was proposed. Land Equivalent Ratios were employed to evaluate two agrivoltaic systems with varying PV panel densities against conventional options, which involve separating agriculture and energy harvesting. Utilizing an array of solar panels, they simulated light transmission at the crop level and employed a crop model to forecast the yield of the crops that were partially shaded. The initial results suggested that AVS might be extremely effective: for the two PV panel densities, an increase in global land productivity of 35–73 % was anticipated. It was published in the Renewable Energy journal in 2011 has been cited 391 times since its publication. Barron-Gafford [56] explored a hybrid system combining solar PV infrastructure with co-located agriculture, addressing energy, water, and food issues through an integrative approach, monitoring soil moisture, irrigation, and plant function. The study found that PV panels provide shading, reducing drought stress on plants, increasing the production of food, and reducing heat stress on the panels. These findings are crucial for future research on food and energy system resilience in the face of future increases in heat and drought-related environmental stress. The study was published in 2019 in the Nature Sustainability journal. It has since been cited 298 times in the Scopus database. Using a comprehensive energy balance model, the advantages of incorporating semi-transparent organic solar cells (OSCs) on the net energy demand of greenhouses in the United States are ascertained by [57]. Their findings indicated that in warm and moderate climates, these systems can have an annual energy surplus. It was also demonstrated that a well-designed greenhouse can minimize the reduction in sunlight entering the space. According to these findings, OSCs are a great option for greenhouse implementation and offer a chance to expand the range of sustainable energy generation technologies available. These findings are published in the Joule journal and has been cited 160 times in Scopus since its publication in 2020.

Furthermore, Trommsdorff et al. [58] evaluated the agrivoltaic technology's technical viability and provided guidance on system design. Additionally, it examined the productivity and behaviour of four crops grown in Germany's largest agrivoltaic research facility, which was established in 2016 close to Lake Constance as part of the Fraunhofer Institute for Solar Energy Systems ISE's APV-RESOLA research project. The facility yielded an electrical yield as well. The Land Equivalent Ratio increased by 56 % in 2017, but the agrivoltaic system significantly increased productivity by nearly 90 % in 2018. This highlights the potential of agrivoltaics to tackle climate change and land scarcity in the 21st century. The study has been cited 119 times and is published in Renewable and Sustainable Energy Reviews journal. A study conducted by Pascaris et al. [59] on solar industry professionals revealed that dual use solar projects can maintain agricultural interests, boosting local support for development. This potential boost in community acceptance is expected to be crucial for upcoming solar projects, particularly in areas where development may pose a danger to interest in agriculture. The study reveals the interconnectedness of social acceptance and market acceptance in agrivoltaics. It emphasizes the need for community acceptance and favourable local regulatory environments for technology growth. These aspects, along with their opportunities and challenges, can guide decision-making to support agrivoltaics and photovoltaic development. There study was published in the Energy Research & Social Science journal in 2021 and has been cited 96 times. Li et al. [60] also examined the main determinants of farmers' propensity to adopt photovoltaic agriculture, including their behaviour, willingness, and willingness-behaviour consistency. China conducted a survey involving 643 participants. Nineteen influencing factors were tested with the bivariate probit model and the binary logistic regression. The study found that 37.1 % of farmers had consistent adoption willingness and behaviour for photovoltaic agriculture, while 62.9 % had inconsistent behaviour. The main variables affecting adoption varied, with the cost of investment negatively impacting farmers' willingness. However, perception of usefulness and technical training positively impacted adoption. The study was published in 2020 in the Energy Policy journal and has been cited 54 times.

Liu et al. [61] investigated a novel and cutting-edge competitive edging development that exists in the agrivoltaics industry. A new photovoltaic system for agriculture was demonstrated, combining diffractive interference technology with concentration photovoltaics (CPV). The system made it possible to generate electricity and use the land for agriculture in a very economical manner. It discussed the test results of the novel agricultural photovoltaic system with plants growing underneath. The CPV system's average efficiency was 6.80 %, while the agriculture photovoltaic system's average efficiency exceeded 8 %. These findings were published in the Solar Energy journal in 2018 and has been cited 54 times. Similarly, the study by [62] added a new dimension to the concept of agrivoltaics by employing tinted semi-transparent solar panels. This allowed for the selective use of various light wavelengths instead of just solar sharing. Spinach and basil were tested for agrivoltaic growth. The production of biomass per unit of solar radiation increased by 68 % with a 63 % increase in the ratio of biomass from leaves and stems to roots when agrivoltaics with tinted solar panels were used. The study is published in the Advanced Energy Materials journal with a total citation of 51 since its publication in 2020. In addition to system-relevant design, Ravishankar et al. [63] took into account plant growth under organic solar cells (OSCs). Three distinct OSC active layers with varying transmittances were compared and their effects on red leaf lettuce growth were assessed while it was grown under semi-transparent organic solar cells (ST-OSC) filters. The study found no significant differences in lettuce fresh weight and chlorophyll content under OSC filters. OSCs can control greenhouse temperature and light, impacting thermal load, plant growth, and power production. This trade space in design is examined and illustrated. These findings are available in the Cell Reports Physical Science journal and has been cited 46 times in the Scopus database since its publication in 2021.

Li et al. [64] developed a holistic system model to evaluate urban farming systems' efficiency in terms of economic and environmental performance, energy and material consumption, and net present value, using a multi-dimensional assessment model to measure water consumption, land occupation, CO_2 emissions, and net present value. The case study explored alternative farming systems in Singapore, focusing on composted food waste, solar photovoltaic energy, and glass-enclosed versus window-free designs. The study found that plant-factory farming systems with solar photovoltaic cells and beer residue fertilizer is a sustainable solution. This paper has also been cited 45 times since its publication in the Journal of Cleaner Production in 2020. Miskin et al. [65] proposed the idea of "aglectric" farming, which involves sharing agricultural land sustainably for the joint production of food and energy, in order to ease land limitations. They suggested installing photovoltaic systems on agricultural land. The suggested solar aglectric farms, either by themselves or in conjunction with conventional wind farms or solar parks, may offer a way to create a sustainable renewable economy that can support the planet's population of over 10 billion people. These findings are published in the Nature Sustainability journal and has been cited 44 times since its first publication in 2019. Proctor et al. [66] provided a reduced-order upper-bound cost appraisal for the extensive installation of solar power plants in the US. They discovered that if less than 1 % of the budget of the United States of America is allocated to infrastructure development at rural area each year, then 20 percent of the nation's electricity needs can be satisfied by AVS. Agrivoltaic system installation on a large scale can result in more than 100,000 new jobs being created in rural areas and a reduction in CO_2 emissions equal to the elimination of 71,000 vehicles from the street daily. Their paper has been cited 41 times since its publication in the Sustainability journal since 2020.

Similarly, [67] offered a potential route forward for the development of organic photovoltaics in the direction of greater market size and commercial success. Via the Shockley-Queisser-Limit, detailed balance assumptions, and the assumption that there is no absorption in the visible part of the AM 1.5G solar spectrum, a power conversion efficiency of 17 % was projected. Organic compounds with good spectral compatibility with chloroplast photosynthetic action spectrum supported the proposal. These results are published in Advanced Energy Materials journal and has been cited 40 times since its publication in 2020. Riaz et al. [68] compared the performance of vertical East/West bifacial farms to conventional North/South mono-facial farms. It found that, if the density of the PV array is reduced, the vertical farm generates nearly the same output energy and photosynthetically active radiation as conventional farms. The study identified advantages of vertical bifacial farms over conventional mono-facial farms in array density, PAR deficit, and energy output, with unique benefits like less land coverage, less equipment obstructions, PV resistance, and lower costs. IEEE Journal of Photovoltaics published these findings in 2021 and has been 39 times. In a two-year study, [69] compared the pasture production and lamb growth in solar pastures with AVS to conventional open pastures in Oregon. In the spring of 2019, weaned Polypay lambs experienced growth of 119 and 120 g $head^{-1}\ d^{-1}$ in open and solar pastures, respectively ($P = 0.90$). Both open pastures (1.3 kg $ha^{-1}\ d^{-1}$) and solar (1.5 kg $ha^{-1}\ d^{-1}$) produced liveweights that were not significantly different from one another ($P = 0.67$). Low pasture density in solar pastures resulted in 38 % less herbage yield than open pastures, but still achieve similar spring lamb production despite lower herbage mass due to higher forage quality. Frontiers in Sustainable Food Systems journal published these findings in 2021 and is cited 32 times.

Also, [70] provided the technical, environmental, and financial analyses to support an agrivoltaics concept's viability. Pasture-fed rabbit farming served as the inspiration for the innovative agrivoltaic system's concept design. The study suggested that rabbit-photovoltaic farming can significantly reduce greenhouse gas emissions from agriculture. It suggested co-locating solar farms and rabbit farms as a feasible form of agrivoltaics, offering a high-value agricultural product with less environmental impact than cattle and increasing site revenue by 2.5 %-24.0 %, depending on location and rabbit rental/ownership. The Journal of Cleaner Production published these results in 2020, and it has been cited 31 times. The research published by [71] examines the features of the current water pumping system, which is powered by both conventional electrical power and solar photovoltaic energy. The existing 2 HP water pump was powered by thin film Cd-Te solar panels. Results from their study showed that the solar-powered water pump performed on par with the conventionally powered pump. Solar water pumps have a significantly higher efficiency than water pumps powered by traditional electricity. As opposed to 65 LPM with the conventional power method, the maximum flow rate achieved was 69 LPM. These findings can be found in the Energy Procedia and it has been cited 28 times since its first publication in 2016. In another study, the region in southeast Spain that has the highest concentration of greenhouse gases (GHG) in Europe, according to [72], is where PV systems should be installed. The results of a sensitivity analysis indicate that farms can earn more money when this technology is used in the self-consumption scenario, with the highest possible return being 52.78 % and the lowest being 0.88 %. The study indicated that implementing this technology on greenhouses in Spain could lead to a 38 % reduction in greenhouse gas emissions by 2030 and nearly meet the official target of 20 % renewable energy by 2020. The Energies journal published these findings in 2017 and has been cited 27 times.

Patel et al. [73] also proposed an solar-agri-electric model. Dust removal from the solar panels allows for the irrigation of agricultural produce beneath them with water used for solar panel washing. The 3 MW solar project, registered under the clean development mechanism, reduced CO_2 emissions by 0.1 million tonnes over 25 years by recycling 78 lakh liters of water annually as well as trapping 250 tons of carbon dioxide in vegetables. Post-harvest residues were utilized for fodder, compost, and organic fertilizer, promoting sustainability and creating jobs for 215 people, including 156 women, from four villages. These findings are published in the Journal of Solar Energy Engineering, it has been cited 24 times since its publication in 2018. Rubio-Aliaga et al. [74] offered a multifaceted characterization to assess how well solar energy integration from photovoltaic (PV) systems integrates with groundwater pumping needs. A comprehensive situation where the significant impact of numerous factors, like water needs, aquifer depth, or irrigation area, were explicitly taken into consideration and was provided by comparing alternative solutions under the economic, energy, and environmental aspects. The findings have been cited 23 times since it was first published in the Renewable Energy journal in 2019. Uldrijan et al. [75] evaluated photovoltaic power plant (PVPP's) vegetation in order to ascertain its possible significance for the nearby ecosystem. The phytocoenological releves method was employed to assess the vegetation. Two distinct locations were captured: beneath and in between PV panels. Plant species were categorized into groups based on how they affected the ecosystem. According to their study, low-growing plant species, including native, entomophilous, and unrelated species, have the best erosion control effects for PVPP operation. Perennial grasses and perennial herbs were recommended for areas between PV panels and beneath them, as they have limited pollen production and pollen allergies. Ecological Engineering journal published these findings in 2021 and it has been cited 22 times.

Fernandez et al. [76] analyzed the energy yield of APV systems in agricultural greenhouses on a worldwide scale. They used a novel dual APV model to conduct the study, which is projected for 15 representative plant cultivars from five distinct significant socioeconomic families of crops— Fabaceae, Cucurbitaceae, Poaceae, Solanacae, and Rosaceae—in four typical localities with great crop cultivation greenhouse implantation, namely, Pachino (Italy), El Ejido (Spain), Vicente Guerrero (Mexico), and Antalya (Turkey)—and for forty-five representative locations. The study found that APV systems can achieve 68 % transparency without significantly affecting crop photosynthetic rate, generating an average of 135 kWh/m^2 of energy per year, with a favorable scenario of 200 kWh/m^2. The Applied Energy journal published these findings in 2022 and it has been cited 22 times. Farfan, et al. [77] defined a new unit that is indicative of the suggested annual intake of vegetables per person and offered an alternative to conventional agriculture that is supported by a shift to a RE system. The study suggests that by 2050, 55.4 million container-sized agricultural units could be powered by 5 % of the projected electricity generation from photovoltaic, biomass, wind, and waste-to-energy, providing 24.4 % of the global population with vegetables. These findings are published in the

Renewable and Sustainable Energy Reviews journal and has been cited 22 times since 2019. Xie et al. [78] assessed the financial feasibility of using diesel fuel and solar PV for irrigation in sub-Saharan Africa, calculating life-cycle costs and comparing their cost-effectiveness across various cropland scenarios. The study's findings demonstrated the potential of solar photovoltaics as an energy source to assist the development of groundwater-fed irrigation. It is often possible to power groundwater pumping for irrigation more cheaply with solar energy than with diesel, especially in central and southern Africa. The Earth's Future journal published this finding in 2021 and has been cited 21 times.

In the study of [79] published in the Applied Energy journal, the authors examined how the surface temperature of solar PV modules and the microclimate of solar farms could be affected by agrivoltaic design elements. In order to study the impact of evapotranspiration, ground albedo, and panel height at a site of a solar PV, they created a computational fluid dynamics (CFD)-based microclimate model and tested it against a wealth of experimental data. According to the study, installing an agrivoltaic solar farm four meters above the ground can lower the temperature of the solar modules by up to 10 °C. Panel height and ground conditions significantly impact cooling. The research suggests that agrivoltaic systems could help address the world's food and energy crisis by increasing solar PV conversion efficiency. The study has been cited 20 times since 2022. Casares de la Torre et al. [80] also published a study in the Renewable Energy journal in 2022, an analysis was done on how photovoltaic systems with north–south horizontal trackers could be converted into AVS by growing tree crops in hedgerows in between the collector rows. The crop's shading on the solar panels was specifically examined. A novel tracking/backtracking approach was proposed to prevent crop shading when the solar panels reach the crop's no-influence zone. In Cordoba, Spain, an agrivoltaic plant with olive groves and north–south horizontal trackers can raise the Land Equivalent Ratio from 28.9 % to 47.2 %. This suggests that PV installations can be converted to agrivoltaic ones, integrating renewable energy sources into a more sustainable agricultural model. The paper has been cited 20 times since publication. Also, [81] offered a cutting-edge irrigation control feature for their solar-powered water pumping system. In order to automate and wirelessly control irrigation and lower labor requirements, humidity sensors and a global system for mobile (GSM) module were installed. The researchers developed a sustainable solar-powered system that uses wireless data from sensors to provide farmers with timely agricultural seeding and harvesting, reducing labor costs and addressing soil erosion, water waste, and insufficient irrigation. The findings are published in the 2019 International Symposium on Recent Advances in Electrical Engineering (RAEE) and is cited 20 times.

Boutelhig et al. [82] determined the ideal configuration for a direct coupling Photovoltaic Pumping System (PVPS) to meet the daily average demand of a remote farm in the Hassi-Gara region. The farm is located approximately 110 km south of Ghardaia, with well heads and boreholes ranging from 10 to 40 m. The study identified two direct coupling (PVPS) configurations for the supply of water: the Shurflo (130 W) submersible DC pump, powered by Isofoton modules, suitable for medium daily water discharge less than 4 m^3, and the Water Max A64 (300 W) submersible DC pump, powered by Isofoton PV modules, suitable for 6–8 m^3 daily water volume. These findings are available in the Energy Procedia journal and has been cited 18 times since 2011. Todde et al. [83] employed a life cycle assessment (LCA) methodology to assess the total energy demand as well as the environmental impact of three autonomous photovoltaic irrigation systems, with power outputs ranging from 40 kWp to 360 kWp. The investigation revealed that the annual embodied energy per unit of PV power varies based on the PV generator's capacity, with carbon dioxide effects ranging from 72.6 to 79.8 kg CO_2e/kWp. PV modules produce 80 % of primary energy in the PV irrigation system. The study also shows an inverse relationship between PV power size and energy and carbon payback times. These findings are available in the Energies journal and has been cited 18 times. According to ISO/TS 14067:2013, [84] assessed the carbon footprint of 0.5 kg of sweet cherries enclosed in a polyethylene terephthalate (PET) clamshell. The study evaluated the entire agricultural supply chain, from the nursery through the disassembly stage to the processing stage in businesses situated in the Apulia region. The study found that agricultural management and fruit processing contribute to the global warming potential of 0.584 kg CO_2eq over 100 years. The largest impacts during the orchard phase were electricity used for irrigation, manure transportation, plowing, and nitrogen fertilizer production. The Journal of Cleaner Production published findings in 2019 and has been cited 18 times. Also, Cosgun [85] examined Turkey's agrivoltaic system's potential. Agrivoltaic systems in Turkey combine crop cultivation and electricity generation on land, requiring approximately 20.000 m^2 for 1 MW of electricity. Vegetables make up 25 % of Turkey's agricultural produce, making them suitable for PV panel arrays. The Energy Report journal published these findings, and it has been cited 17 times since 2021.

Additionally, A sustainable energy plan for an energy-deficient village was unveiled by [86]. It aims to maximize the use of electrical energy resources. The village of Nangal, in Punjab, India, close to Barnala, has been selected. A coordinated solution was also presented and examined for solar PV-powered water pumps that are used for street lighting, irrigation, and village water supply. The parametric evaluation of the suggested HRES system has shown that the computed energy cost and total net present cost are, respectively, $0.032/KWh and $76,837. These findings are available in the International Journal of Low-Carbon Technologies and has been cited 17 times since 2021. Homayouni et al. [87] examined the combined cooling, heating, and power (CCHP) requirements of a autonomous greenhouse in Iran using hybrid solar hydrogen energy systems to achieve sustainable farming through process optimization. From an environmental perspective, 83 % to 100 % of emissions can be avoided by implementing hybrid energy systems. The findings are available in the International Journal of Green Energy and has received 17 citations since 2016. An integrated water-electricity-crop co-production system (WEC^{2}P) that is self-sufficient and powered by solar energy was described by [88]. WEC^{2}P was designed with the atmospheric water adsorption–desorption cycle in mind. This cycle can be used to: (1) produce cooling power for PV cells to enhance their power generation capabilities; or (2) using atmospheric water vapor to sustainably produce fresh water to support crop growth. The WEC^{2}P significantly reduced PV panel temperature and power generation by up to 9.9 % during a three-month outdoor field test, generating water for irrigating water spinach in a Saudi Arabian integrated plant-growing unit. The Cell Reports Physical Science journal reported these findings in 2022 and has been cited 16 times. A hybrid micro-concentrator module with tracking integration was demonstrated by Nardin et al. [89], capable of harvesting albedo, diffuse, and direct irradiance components. It uses a planar micro-tracking mechanism for installation in static frames and biconvex 180x lens arrays, achieving 29 % efficiency outdoors. Two architectures were developed for harvesting diffuse irradiance: a translucent one for dual-land-use applications and a hybrid one with monofacial or bifacial Si cells. Simulations showed that the hybrid architecture produces more energy annually than a 20 % efficient PV module, with bifacial gains potentially increasing energy yield by 30 %. They also analysed about the translucent modules' potential for dual-land-use applications, like greenhouse integration for agrivoltaics. The study was published in the Progress in Photovoltaics journal and has been cited 16 times since 2020.

Imran et al. [90] investigated the most effective single-axis tracking systems for photovoltaics that can precisely balance the amount of sunlight received by crops and photovoltaics. Bifacial panel arrays in two distinct PV orientations— east/west (E/W) and north/south (N/S)—were subjected to the single-axis tracking schemes. They suggested specialized solar tracking plans that, depending on the needs of the crops, alternate between regular and reverse sun tracking during the day. The study is available in the 2020 47th IEEE Photovoltaic

Specialists Conference (PVSC) and has been cited 15 times. Pascaris [91] also utilized Legal Framework Analysis to pinpoint opportunities and obstacles for a thorough legal framework that would support agrivoltaics in the United States. The study suggested a detailed legal framework for AVS should integrate state and local land use regulations with federal and state energy financing programs, primarily through a state-level feed-in tariff and local government allowances. These findings are available in the Energy Policy journal and has been cited 14 times since 2021. Xie et al. [92] recommended converting a decommissioned thermal power plant in Ningxia, China, into a hybrid photovoltaic/solar chimney (PV/SC) power plant with agriculture. PV and SC power plants significantly increase daily capacity, reduce CO_2 emissions, generate revenue, and have a 14.2 % comprehensive solar energy conversion efficiency. With agricultural production, generation of power, and heating all taken into account, the converted plant has a remarkable solar energy conversion efficiency of 14.2 %—36.9 % greater than that of a corresponding traditional PV power plant. This study has received 14 citations and is available in Renewable Energy journal.

Hu [93] used a thorough case study and a variety of secondary sources, incorporating details on 421 solar projects, to examine the growth of solar power in China from the perspective of political ecology. The study revealed that China's agrivoltaics industry has been fueled by solar extractivism, characterized by extensive agricultural land acquisition, solar electricity generation, dominance of renewable industries, state involvement, and discriminatory enforcement. The study has been published in the Energy Research & Social Science journal and has been cited 13 times since 2023. Riaz et al. [94] analysed food-energy productivity requirements and optimized PV array row density for fixed tilt bifacial PV for a specific crop. It compared vertical tilted bifacial PV arrays with North/South faced arrays at fixed optimal tilt. The effect of tilt angle on crop shadowing and energy productivity as well as the relative productivity of food and energy at a particular array density were also investigated in their study. The 2020 47th IEEE Photovoltaic Specialists Conference (PVSC) published these findings and has been cited 13 times since publication. Shatar et al. [95] presented a proof of concept for controlling energy usage in a precision agriculture system using a hybrid photovoltaic-thermoelectric generator (PV-TEG) system. It compared the power output of a stand-alone solar photovoltaic system with the hybrid system's output. The study used mathematical modeling using Matlab/Simulink to determine the feasibility of hybrid systems. 2018 IEEE 7th International Conference on Power and Energy (PECon) published these findings, and it has been cited 13 times.

Finally, the study of [96] created income and cost models for solar-powered greenhouses and evaluated their economic performance by examining the impact of the investment and utilizing metrics such as payback period, internal rate of return, and net present value. The study found that large photovoltaic greenhouses with high installed capacity are unaffordable for farmers and large corporations due to high investment costs and land use. It recommended no more than 15 MW installed capacity. The financial gain from these greenhouses decreases with high bank loans usage. The Journal of Renewable and Sustainable Energy published these findings in 2017, it has been cited 13 times. Moore et al. [97] explored stakeholder opinions on utility-scale solar power development on farm lands and the institutional dynamics influencing siting decisions, contributing to the social science literature on RE and public consent. The study explored key epistemic paradigms influencing stakeholder conflict and provides a conceptual map of institutions and players influencing solar siting on agricultural land. It also explored perceptions of the agricultural community, local farmland renters' decisions, prime versus lower quality farmland, farmland ownership and farm financial viability. Energy Research & Social Science published these findings in 2022 and it has been cited 12 times. Jing et al. [98] suggested a multidisciplinary assessment framework that integrates solar power simulation, biogeochemical simulation, and Geographic Information System (GIS) to maximize the potential of urban rooftop agrivoltaics. A case study in Shenzhen, China, found that implementing AVS on rooftops could produce enough lettuce to meet the city's demand. Solar PV, with an average capacity of 2106 MW, generates 1899 GWh of electricity annually, generating 0.2 % of the city's total electricity consumption. Additionally, agrivoltaics require 4.11×10^6 tonnes of freshwater per year for irrigation. The Energy journal published these results in 2022, it has been cited 11 times. In addition to prioritizing the most important variables for the project economy, Jing et al. [99] suggested an economic analysis framework to compare the viability of both agrivoltaic and aquavoltaic systems. According to the study, China's solar projects have an average simple payback period of 6.2–6.6 years for agrivoltaics and 9.5–10.1 years for aquavoltaics, influenced by feed-in tariffs, solar resource richness, and capital cost. The combined potential for agrivoltaics and aquavoltaics implementation in China is 112 GW for agrivoltaics and 564 GW for aquavoltaics. The findings of this paper are available in the Renewable Energy journal and has been cited 11 times since 2022. Benzaouia et al. [100] demonstrated a practical energy-management and control approach for a standalone water pumping system powered by photovoltaic batteries intended for agricultural use. The system uses lead-acid batteries as a secondary energy source and solar PV modules as its primary energy source to power the centrifugal pump via brushless DC motor. Comparing the results to the traditional Perturb & Observe (P&O) method, it was evident that the attained results had a faster convergence performance. The suggested energy management algorithm's performance in random meteorological conditions was validated by computer simulation findings. The findings are available in the ICEERE 2020: Proceedings of the 2nd International Conference on Electronic Engineering and Renewable Energy Systems, and it has been cited 10 times.

Conceptual structure analysis

The conceptual framework draws attention to the main ideas, subjects, and connections found in the information gathered for the bibliometric analysis. The conceptual framework of this study is centred on factorial analysis of keywords, thematic evolution, and thematic map.

Thematic map, evolution, and factorial analysis

The research themes depicted in Fig. 3 are derived from the conceptual framework of the documents that were part of the Bibliometric analysis. The themes of the research are represented by the clusters in the graph, and their size reveals how closely each cluster relates to the total number of keywords. A distinct theme is represented by each quadrant in the figure. The motor themes, which are distinguished by high centrality and density, are depicted in the figure's upper-right quadrant. The theme map's upper-left quadrant, which represents niche themes, is divided into two sections: one for high density and low centrality. Furthermore, the lower-left quadrants of the thematic map depict the emerging themes, which are characterized by low centrality and density, whereas the themes positioned in the lower-right position of the map are named basic themes [101,102].

In the *Motor themes* there are two clusters, the biggest cluster which has the highest centrality consist of words such as photovoltaic, solar energy, and agrivoltaic, the other cluster which is relatively denser and smaller has themes such as circular economy and photovoltaic energy.

The *Niche quadrant* has four clusters, the densest cluster consist of themes like greenhouses, organic photovoltaics, controlled environment agriculture, energy balance modelling and semi-transparent solar cells. Organic photovoltaics (OPV) that are semi-transparent show promise as greenhouse integration solutions for power generation with negligible effects on crop growth. With the recent finding of non-fullerene organic small molecule acceptors, the power conversion efficiency of the opaque solar cell has reached 18 %, nearly commercial level [103–105]. Moreover, semi-transparent OPV has a comparatively high average visible light transmittance (above 20 %) and a power conversion efficiency (PCE) of over 13 %. Additionally, OPVs offer numerous special

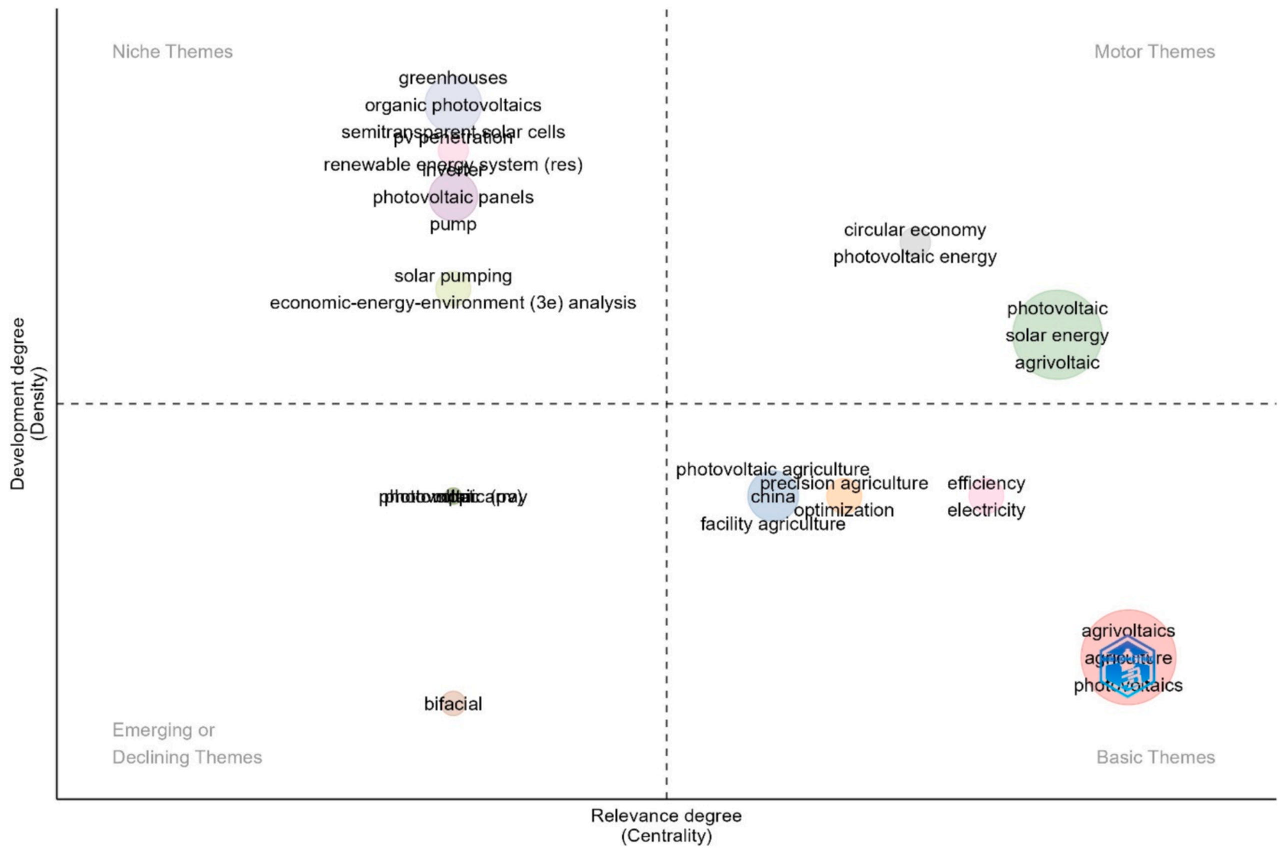


Fig.3. Thematic map for author keywords.

advantages over inorganic photovoltaics. Because of their solution processability, OPVs can be manufactured on a large-scale using roll-to-roll printing for large-area depositions [106]. Its wavelength selective absorption spectra make OPV technology unique [107]. When it comes to capturing photons up to an absorption edge, inorganic solar technology is competitive with continuous wavebands [108]. The next densest cluster in the Niche quadrant has words such as PV penetration, and renewable energy system. The third cluster has keywords such as inverter, photovoltaic panels, and pumps, this cluster basically looked at the use of power from PV panels to pump water for irrigation purposes. The last cluster is made of words such as solar pumping, and economic – energy – environment (3E) analysis, in this cluster the technical, economic viability and the environmental impact of agrivoltaics systems are assessed.

The *Emerging/Declining quadrant* has two clusters with relatively equal centrality; however, the densest cluster has themes like photovoltaic array, and MPPT. The second cluster has one word, i.e., bifacial, a more recent development in the solar industry are bifacial solar panels, which are more expensive but more efficient because they can collect diffused sunlight on both sides of the panel. The combination of bifacial technology and agrivoltaics has enormous potential to increase the efficiency of electricity generation using available space. Bifacially oriented solar systems are a relatively new invention and can best be described as emerging, in contrast to conventional single-sided solar panels that are set vertically on farms and other agricultural facilities. Because plants require sunlight to thrive, the range of crops that can be grown under conventional solar panels is limited; however, bifacial vertical solar modules facilitate the growth of a greater variety of plants. Potatoes and hay are two excellent crops for this technology. Higher-growing crops, like corn, might obstruct the panels, necessitating a taller installation that may cost extra. Studies have also demonstrated other advantages, like water conservation for irrigation [109].

The *Basic themes* quadrant also has four clusters, the biggest cluster consist of themes such as agrivoltaics, agriculture, and photovoltaics, indicating studies that focused on agrivoltaics, the second cluster also has words such as photovoltaic, China, facility agriculture, and solar farming. The third cluster has themes such as precision agriculture, and optimization. Precision agriculture, also referred to as site-specific crop management or precision farming (PF), is a farming management concept that offers a comprehensive system approach to managing the crop and soil variability within a field in order to maximize yield and quality, minimize costs, and lessen environmental impact. The last cluster in this quadrant has words such as efficiency and electricity.

VOSviewer generates two different maps: one for network visualization (see Fig. 2**b**) and the other for overlay visualization (see Fig. 4). The two-dimensional distance-based map used in both visualizations indicates the degree of relationships between the objects according to their distance from one another. Stronger associations are indicated by a greater distance and vice versa. Conversely, a closer distance indicates a stronger bond. It is identified by a label and a circle, the size of which reflects the importance of the keyword. While overlay and network visualizations use different colours to represent different kinds of information, they both use the same bibliographic mapping. The network visualization provides information about keyword cluster groupings, while the overlay visualization displays each term's average yearly publication [110]. The map with overlay visualization shows which themes are still in use and which have been developed or researched over time.

Different colour ranges are used to represent the years. The subjects covered during the study years are shown in blue, green, and yellow. The newest publications are represented by light colours, and the older publications are marked with darker colours. From the overlay visualization of all keywords, research on the topic is maturing and evolving, moving from small scale power generation for irrigation purposes (i.e.,

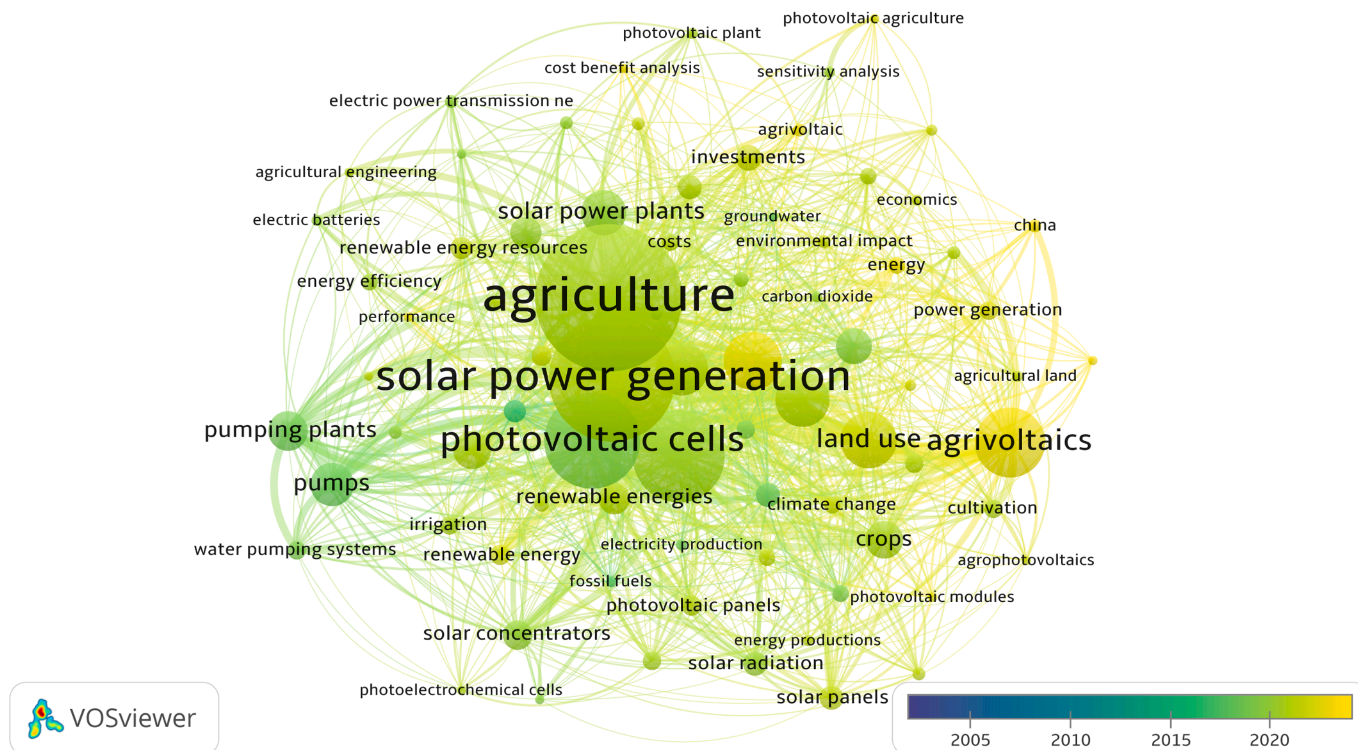


Fig.4. Overlay visualization of all keywords.

solar pumps) to large-scale electricity generation with emphasis on dual land use for both energy and food production.

Finding a set of variables' underlying structure can be done statistically using a method called factorial analysis. By decomposing intricate relationships into more manageable parts, it is utilized to identify the critical variables and the ways in which they interact. Marketing, engineering, sociology, psychology, and other disciplines all make use of the factorial analysis, which is a potent tool. By figuring out the underlying causes of the observed relationships, a factorial analysis aims to minimize the number of variables in a dataset. These elements, also referred to as latent variables, are the fundamental reasons behind the observed variables. Factorial analysis reduces the number of variables, which facilitates the understanding of the underlying structure of the data and the prediction of future relationships [111]. The Multiple Corresponding Analysis (MCA) was utilized to create the factorial map displayed in Fig. 5. On two dimensions (Dim. 1 and Dim. 2), the figure shows words or terms, their corresponding scores or loadings, and a cluster assignment. The relative contribution or importance of each

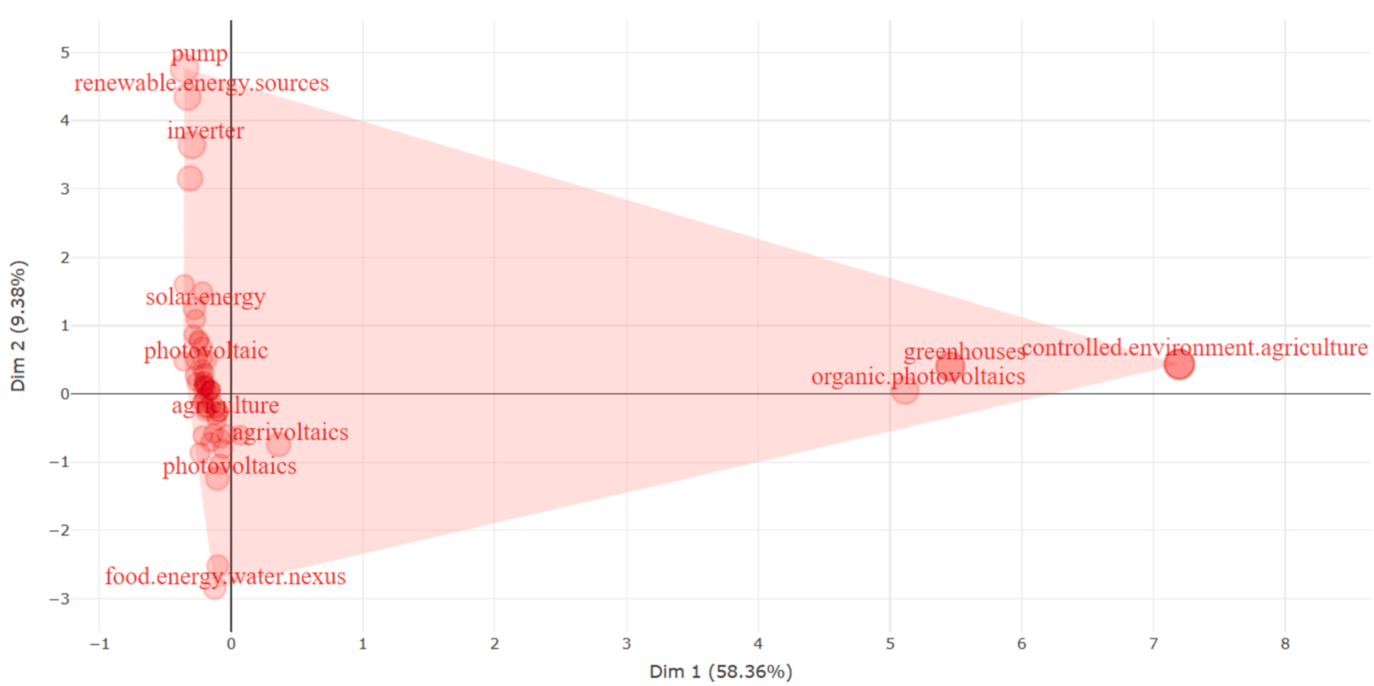


Fig.5. Factorial analysis for author keywords.

word to a given dimension is indicated by the loadings or scores on those dimensions. The relative positions and distribution of the dots along the dimensions are utilized to explain the results; in Fig. 5, the more similarly distributed the words are, the closer together they are displayed. In this analysis, terms that have garnered more attention recently are more evenly distributed and closer to the centre of the map, whereas less-discussed research topics are associated with more evenly distributed terms [112]. From the results displayed on the map, keywords such as solar energy, agriculture, photovoltaic, agrivoltaics, food energy, water nexus, pump, and renewable energy are found to be closer to the centre of the map, and more evenly distributed. These keywords are close to each other because a large proportion of the studied documents used them together. However, themes such as organic photovoltaics, greenhouses, environment, control, and agriculture that are distant from the centre have a small fraction of articles that use these words, which means these areas are less discussed and hence can be looked at going into the future.

International collaborations and sources

Sankey diagrams are a widely used visual aid for depicting material or energy flow in networks and processes. They incorporate quantitative details along with a visual representation of the flow, connections, and transitions. Weighted and directed graphs with weights that guarantee flow preservation are a feature of Sankey diagrams. Every node has input weights that are equal to corresponding output weights. These diagrams make it possible to explore relationships and communication patterns as well as visualize processes. Fig. 6 shows a three-field plot based on a Sankey diagram that illustrates the relationships between nations, institutions, and keywords. Within the collaboration network, the height of the rectangle nodes corresponds to how frequently a particular nation, organization, or keyword appears. The number of connections is directly correlated with the width of the lines connecting the nodes [113,114]. Based on the findings, it is clear that the North Carolina State in the USA has the highest connections, followed by institutions in China. The USA and China are leading agrivoltaics research due to climate change concerns, transitioning to renewable energy sources, and government programs promoting technology adoption.

The results suggest that China and the United Kingdom engaged in the highest number of collaborations with a frequency of 3. China and Sweden (frequency = 2), India and Hong Kong (frequency = 2), Iran and Kazakhstan (frequency = 2), and USA and Finland (frequency = 2). The remaining countries involved in collaboration on the topic recorded single frequencies with their collaborating countries.

Future research recommendations

Based on the findings of this study, the following future research directions can be pursued:

- The viability of animal-based agrivoltaic systems is challenging due to limited data and completed projects. However, studies suggest that raising animals and producing electricity together is feasible. Further research is needed on longer rearing periods and dairy farming, as heat stress can lower milk production and cows are raised on large agricultural land. This field has significant potential for food and electricity production, potentially encouraging the growth of agrivoltaics in conjunction with animal husbandry [24].
- Shade-tolerant plants are the most economically viable choice when it comes to agricultural practices, as the microclimatic conditions of PV systems greatly influence them. Important factors include crop temperature, light saturation point, UV damage, evaporation rate, and irradiation capture efficiency. Few studies have looked into these connections [10]. Modeling the microclimate beneath photovoltaic arrays under various orientations and placements is necessary to choose crops that are adaptable. Experiments in the field and simulation are needed to determine the ideal growing conditions for plants, including the length and timing of shade periods.
- Most APV studies lack cost analysis and only considered levelized cost of energy in economic analysis. Further research is needed, particularly on crop rotation and PV degradation.
- Sheep-based agrivoltaics is widely used, but more experimental trials are needed to increase knowledge in sheep meat and wool production. Future studies should explore regional and climatic variability, as well as panel shading effects, on pasture grass growth rate in livestock-based systems [12].

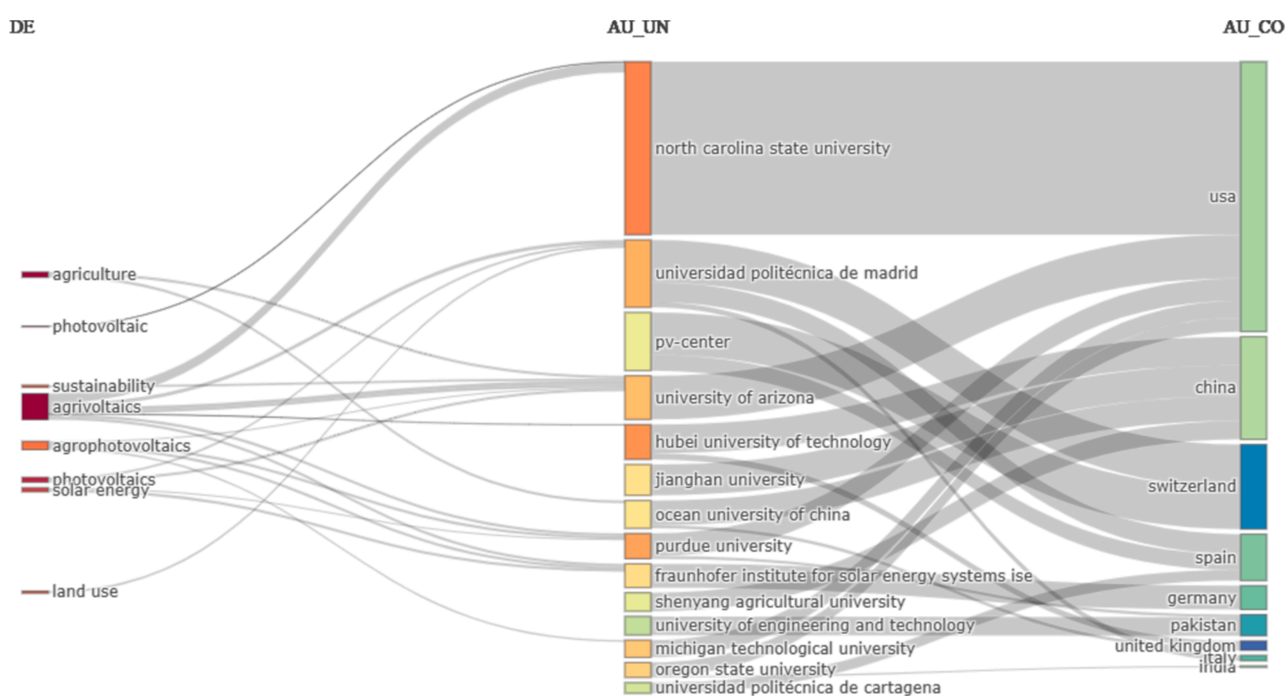


Fig.6. Three field plot.

- APV technology faces obstacles in the form of criticism and possible adverse effects on agricultural yield when it comes to widespread adoption. Agrovoltaic systems mitigate food-energy conflicts and help prevent land loss, but they can also cause disputes between groups due to changes in the topography of the landscape [1]. To fully comprehend the effects of crop types and climate on the viability of agrovoltaic systems worldwide, more research is required.
- Few research using solar panels that separate the light spectrum have been done thus far. Thus, it might be worthwhile to assess this technology, which restricts direct plant shading and permits the wavelengths required for photosynthesis to pass through. Identifying a general shading threshold for plants without affecting yield is challenging due to species, crop location, agrivoltaic array design, and time of year. Therefore, it's recommended to determine each species' ideal daily light integral level before modifying the agrivoltaics system [24].
- Not much work has gone into the development of semi-transparent organic solar cells (ST-OSCs), despite their potential to supply advanced agricultural applications with rooftop and off-grid power supplies [115,116]. A top electrode for semi-transparent OSCs needs to have high visible light and near-infrared conductivity, transmittance, and reflectance. Conductivity and transmittance need to be balanced by the electrode's thickness. Power conversion efficiency and average visible light transmittance can be enhanced via photonic crystal, antireflection coating, optical microcavity, and dielectric/metal/ dielectric structures. On the other hand, expensive devices have intricate structures. For efficient transparent OSCs, more research is required to find semi-transparent top electrodes with the required optical, electrical, processing, low cost, and high stability [117]. Also, future research on the use of organic photovoltaics (OPVs) in greenhouses should consider, seasonal changes, OPVs' effects on plant water and nutrient efficiency, spectral characteristics, degradation over time, and installation techniques [118] to give a broader understanding about the technology on the performance of the agricultural products. Additionally, future studies should explore energy production and consumption dynamics in integrated OPV greenhouse systems.
- Finally, future studies should examine the factors that influence farmers' decisions to install agrivoltaic systems, since farmers' acceptance of these systems depends critically on their ability to make sound business cases and knowledge about these systems can be a major barrier to adoption.

Conclusion and potential research directions

The recent increase in human population and economic activity has intensified competition for land. Crop production occupies about 12 % of the world's land area. The demand for energy, particularly electricity, is expected to increase solar installations, leading to competition for land and agricultural output. Hence, research on the agrivoltaics technology has increased over the years. This study therefore reviewed two decades of studies on the topic using the systematic and bibliometric review methods. The study analysed 155 documents, with research on the topic growing 18.21 % annually, authored by 639 authors, with an average age of 3.99 and 17.51 average citations per document. The study highlights the relevance of the theme "agrivoltaics", as the most frequently used keyword occurring 37 times within the study period, highlighting its potential for sustainability and sustainable land use. Research on the topic is found to be evolving, transitioning from small-scale irrigation power generation to large-scale electricity generation, emphasizing dual land use for energy and food production. North Carolina State University in the United States of America and China are leading in agrivoltaics research due to climate change concerns, transitioning to renewable energy, and government programs promoting technology adoption. Going forward, the effect of PV technology on crop yields and quality has not received much research attention. To assess its suitability in agricultural systems—taking into account crop species, varieties, and climatic conditions—more research is required. Collaborations with innovations in agriculture and photovoltaic technology are also essential. Field experiments can be effectively processed by modelling into universal models that are tailored to particular circumstances and PV system technical implementations. In order to solve societal and environmental issues like land use, food security, climate change, and the demand for energy globally, APV can play a significant role in future agricultural systems [23].

CRediT authorship contribution statement

Ephraim Bonah Agyekum: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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