

Review

Solar Energy Applications in Protected Agriculture: A Technical and Bibliometric Review of Greenhouse Systems and Solar Technologies

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Abstract: This study addresses solar energy applications in protected agriculture, focusing on greenhouses and related technologies. A bibliometric and technical analysis is developed, covering research published between 1976 and 2024, to identify the main trends and challenges in the use of solar energy in controlled environments. The methodology was based on the PRISMA approach, using the Scopus database to retrieve relevant documents. From an initial total of 221 documents, 216 were selected after a filtering and debugging process, ensuring the relevance of the final set. In the analytical phase, the results showed a moderate growth of 3.68% in the annual publication rate, highlighting the impact of research on solar energy's application to air conditioning and energy efficiency in greenhouses. Most of the studies reviewed feature hybrid systems that combine solar energy with other resources, and we highlight both advances in climate control through artificial intelligence and the implementation of photovoltaic and thermal technologies to improve the energy efficiency of agricultural systems. The results also underline the importance of tomato cultivation in the selected studies, reflecting its global economic impact. The conclusions highlight the need for the further integration of energy storage and desalination technologies, especially in arid regions with high solar irradiation, to ensure the sustainability of greenhouses. It is proposed that future research should address the wider implementation of hybrid systems and advanced climate control technologies, optimizing both the use of energy resources and the performance of crops under cover. In addition, it is recommended that international collaboration be strengthened to address technical and climatic challenges in protected agriculture and to expand the adoption of innovative solutions in different geographical contexts.

Keywords: climate control; energy efficiency; greenhouse technology; photovoltaic systems; solar energy; sustainable agriculture



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1. Introduction

Protected agriculture has become increasingly important worldwide amidst growing challenges such as global warming, the environmental crisis, and food insecurity [1]. Climate change has intensified extreme weather events, directly affecting agricultural production in many regions. Prolonged droughts, heat waves, and severe storms are becoming

more frequent, creating an urgent need for more resilient agricultural systems [2,3]. In this context, protected agriculture, which includes greenhouses and crops under cover, provides a controlled environment that protects crops from inclement weather, allowing continuous food production even under adverse conditions [4,5]. Moreover, in a world where the environmental crisis demands sustainable solutions, protected agriculture offers a more efficient use of natural resources, which contributes to reducing the environmental impact associated with conventional agriculture [6]. Globally, this practice has become a key tool with which to address food security, protecting food production in a context of growing demand and limited resources [7,8].

The benefits of protected agriculture are numerous. Among the most outstanding are the increase in crop yields, the reduction in the use of agrochemicals, and the efficient use of water resources [9–11]. By creating a controlled or semi-controlled environment, growers can optimize plant growth, maximizing yields and improving product quality [12,13]. At the same time, by minimizing exposure to pests and adverse weather conditions, protected agriculture significantly reduces the need for pesticides and herbicides, promoting more sustainable and environmentally friendly farming practices while generating healthier food [14].

However, the success of protected agriculture and the achievement of the above-mentioned benefits relates largely to the ability to control the microclimate inside the greenhouses [15,16]. Factors such as temperature, relative humidity, solar radiation, and CO₂ concentration can be regulated to provide an optimal environment for crop growth [8,17]. A controlled microclimate not only improves plant yields, but also allows for extended growing cycles, which is essential to meeting the world's growing demand for food [18,19]. In addition, automation and the use of intelligent technologies such as sensors, climate control systems, and solutions based on the Internet of Things (IoT) allow these parameters to be adjusted in real time, ensuring greater precision in the management of internal greenhouse conditions. [20,21]. This, in turn, reduces dependence on external climatic conditions, improves the efficient use of water and energy resources, and reduces the use of water and energy [22].

Controlling the microclimate inside greenhouses, however, represents a technical and energy challenge. Traditionally, this control has been achieved through the use of heating and ventilation systems that rely on fossil fuels [23]. While these systems are effective, their environmental impact is considerable. The use of fossil fuels not only contributes to greenhouse gas emissions, but also generates high energy costs, posing both economic and environmental challenges [24,25]. In response to these limitations, the development of more sustainable solutions has gained prominence in recent years.

The use of renewable energies, such as solar and geothermal energy, has emerged as an effective alternative with which to supply heating and ventilation systems in greenhouses, considerably reducing dependence on fossil fuels [26]. The integration of photovoltaic systems into the roofs or structures of greenhouses makes it possible to generate enough electricity to cover operating energy needs, thus contributing to the energy self-sufficiency of these medium- and high-technology facilities [27]. At the same time, the implementation of passive ventilation systems [28,29] and the use of thermal storage make it possible to regulate temperature fluctuations without resorting to external energy sources in low- or medium-technology greenhouses. These approaches not only strengthen the sustainability of greenhouses, but also reduce long-term operating costs, improving the profitability and competitiveness of the agricultural sector in a market increasingly oriented towards sustainable practices. In addition, combining these renewable technologies with intelligent control systems could further optimize the energy performance and climate management of greenhouses, establishing a model for protected agriculture in the future [29,30].

Therefore, the objective of this study is to carry out a technical and bibliometric review of the use of solar energy in protected agriculture, with special emphasis on greenhouse systems. To address this objective, a bibliometric analysis methodology is used to identify the main trends in research and development on solar applications in protected agriculture.

Likewise, the most recent solar climate control technologies for greenhouses are reviewed, and we analyze their efficiency, economic viability, and sustainability. This review is expected to provide a comprehensive overview that will support the development of advanced technological solutions for use in protected agriculture worldwide.

2. Materials and Methods

The methodology used for this systematic literature review was based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) approach, which consists of the stages of identification, selection, eligibility, and data extraction [31]. A specific search strategy was developed to identify the most relevant studies released between 1976 and 2024, using the robust academic database Scopus as the main source of information (accessed 8 November 2024) [32,33]. In this study, only peer-reviewed articles that were published in indexed journals, in books, at conferences, and in book chapters and which addressed the topic of interest were reviewed [34]. In addition, a workflow was applied to identify unrelated documents whose title or abstract contained keywords aligned with the general objective of the study search, and which were collected using the equation mentioned in phase 1, but whose specific content was not relevant. This process is illustrated in Figure 1. In addition, a checklist following the updated PRISMA 2020 guidelines is included in the Supplementary Material.

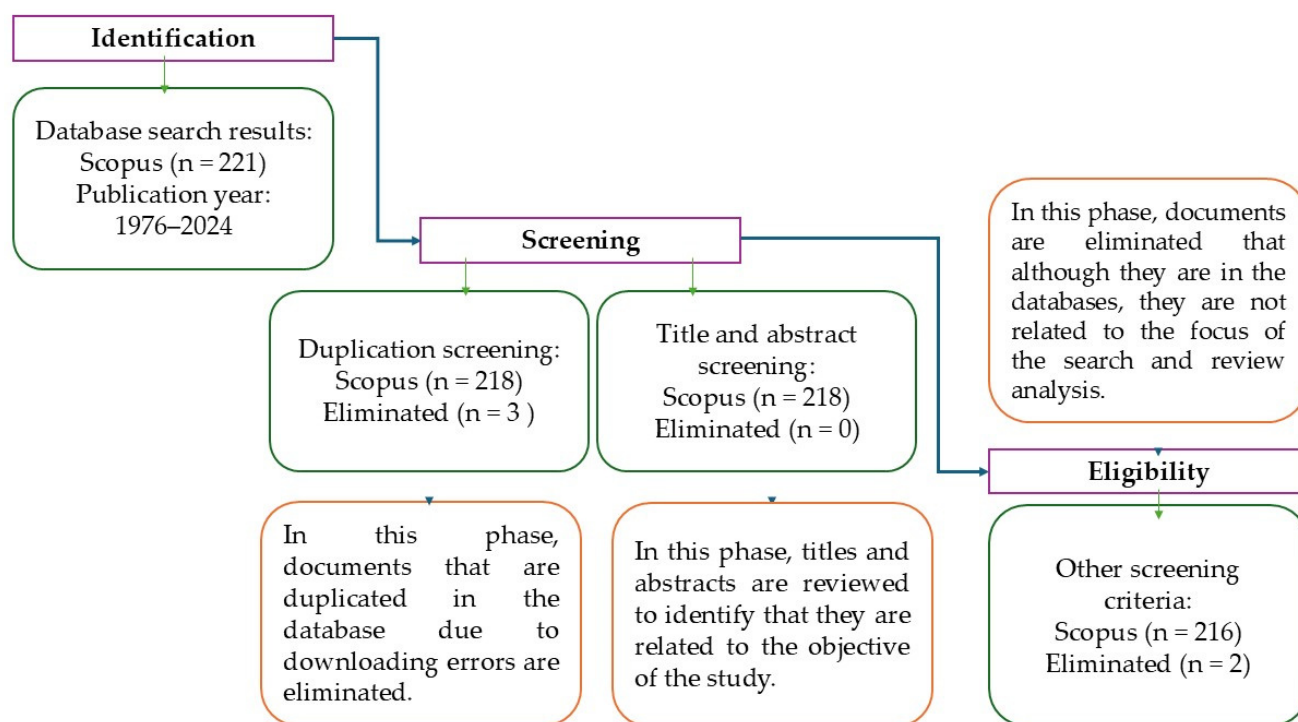


Figure 1. The workflow for the selection of documents received for analysis in this review.

Phase 1. The search and quality control of the information collected

In this phase, the search equation was established to ensure the recovery of relevant scientific papers dealing with the integration of solar energy in protected agriculture and its application in greenhouses. The equation used was as follows: TITLE-ABS-KEY (((“protected agriculture” OR “greenhouses” OR “covered crops” OR “photovoltaic greenhouses”) AND (“solar energy” OR “solar utilization” OR “solar technology” OR “solar panels” OR “solar heating” OR “solar power”) AND (“greenhouse systems” OR “solar-powered greenhouses” OR “solar applications in agriculture” OR “solar-assisted agriculture” OR “solar energy in protected crops” OR “solar climate control” OR “solar energy systems” OR “agrivoltaics” OR “agripv” OR “agrivoltaic”))) AND NOT

("greenhouse gases" OR "carbon emissions" OR "biogas" OR "urban agriculture" OR "carbon sequestration").

This equation was designed to capture a wide variety of topics related to solar energy in protected environments, enabling the identification of papers that analyze both energy harvesting and the use of solar-powered climate control systems for canopy crops. Boolean operators (AND, OR, NOT) were used to optimize the search and avoid irrelevant results related to topics such as greenhouse gasses, carbon emissions, or urban agriculture, ensuring that only research focused on solar-powered agricultural applications was retrieved. The initial equation generated a set of 179 documents, which were further filtered to exclude repeated or out-of-context articles [35], thus reducing the total number of documents designated for technical and bibliometric analysis to 168.

Phase 2. The generation and mapping of the scientific structure of the field of knowledge

In Phase 2, the previously filtered document base was subjected to quantitative and qualitative analysis using R software version 4.3.3, which is from the Bibliometrix package, for the construction of a detailed bibliometric profile. This is a package developed by Aria and Cuccurullo [36]. This analysis included the evaluation of the number of authors, the countries of origin, the number of citations, and the predominant keywords in order to obtain a global overview of the research published in the area. A general summary of the scientific production was generated, making it possible to identify current trends and the authors with the greatest impact [37]. Subsequently, a thematic map showing the structure of the research was constructed based on multi-component analysis (MCA), which facilitated the identification of emerging trends and central themes, such as the use of solar energy in climate control and hybrid technologies for photovoltaic greenhouses [38]. At the same time, VOSviewer software version 1.6.20, was used to deepen the structure of the scientific network by analyzing keyword co-occurrence and co-authorship networks by country and between authors, identifying the most influential collaboration nuclei [39].

Phase 3. Technical analysis of the main documents

This phase consisted of an exhaustive technical analysis of the selected papers, focusing on three main categories: the 10 most cited articles, the 10 most recent articles, and the articles specifically related to tomato cultivation. This approach provided a detailed overview of the most influential lines of research and the most recent technological developments related to the use of solar energy in protected agriculture. The most cited articles were analyzed in terms of their scientific impact, the relevance of their findings, and their contribution to the consolidation of new methodologies in greenhouse design and climate control. On the other hand, the review of the 10 most recent articles provided updated information on emerging trends, identifying new applications of photovoltaic energy and the use of hybrid systems to improve greenhouse energy efficiency. In addition, a specific section was dedicated to the analysis of articles focused on tomato cultivation due to its global economic and agricultural importance [40].

3. Results and Discussion

3.1. General Analysis

The bibliometric analysis reflects a broad and diversified picture of scientific development in the field of solar energy applications in protected agriculture. The period of analysis spans from 1976 to 2024, with an annual publication growth rate of 3.68%, indicating steady, albeit moderate, growth. The total number of documents amounts to 216, distributed in 121 different publication sources, with a total number of 6139 citations. This shows an acceptable level of impact and visibility within the academic field [41,42]. The average age of the papers (15.2 years) suggests that the field integrates both pioneering studies that have maintained their relevance over time and recent research that allows us to identify emerging trends and technological developments in the area [4].

In terms of academic collaboration, there are patterns of co-authorship that highlight the collaborative nature of the field, with 669 participating authors. Only 34 papers were written by a single author, and the average number of co-authors per paper was 3.93, which

reinforces the idea that most research is carried out in multidisciplinary teams that approach the problem from different perspectives. In addition, 15.8% of the documents correspond to international collaborations, which indicates that research on the use of solar energy in controlled environments and protected agriculture has captured the attention of the global scientific community, promoting cooperation between countries to optimize technologies and strategies for microclimate management in this type of production system [43].

With respect to the typology of documents, the preponderance of scientific articles (121) and conference papers (65) shows that the topic is of great interest to both the academic community and the technical–industrial field. The presence of 14 systematic reviews suggests an effort to consolidate existing knowledge, identify research gaps, and establish theoretical bases for future research [44]. Also, the small number of books (1), book chapters (11), and conference reviews (4) suggest that, although research in this field is well established, there are still opportunities to develop compilations and technical manuals that contribute to knowledge transfer and the practical implementation of technologies in agricultural settings by producers operating at various technological levels. Taken together, these results lead to the conclusion that the field presents a balance between high-impact publications and active international collaboration, with a growing focus on the integration of solar energy to improve efficiency, control, and sustainability in protected agriculture.

3.2. Relevant Authors

Table 1 shows the top five authors working in the field of solar energy applications in relation to protected agriculture. This analysis shows the dominance of researchers from the Netherlands, with Sonneveld PJ, Swinkels GLAM, Bot GPA, and Van Tuijl BAJ all being academically affiliated, reflecting the strong scientific input of this region in the development of technologies and innovations for greenhouses and the use of renewable energies. Sonneveld PJ and Swinkels GLAM, both with 9 published papers, show moderate impact in the area, with H-indexes of 9 and 10, respectively, but exhibit high consistency in terms of the number of citations per paper. Bot GPA, with a smaller number of papers (7), has an H-index of 31 and 3729 total citations, consolidating himself as a reference author whose research is widely cited. Friman-Peretz M, from Israel, and Marucci A, from Italy, also have significant roles, although with less impact in terms of citations and a lower H-index score. Marucci has 5 published papers, with an H-index of 20 and a total of 1092 citations, while Friman-Peretz, with 6 papers, has an H-index of 5 and 121 citations in total. Likewise, Van Tuijl BAJ, despite having only 5 papers, has accumulated a significant number of citations (1444) and an H-index of 11, suggesting a high degree of specialization in his area of study. The author Poncet C displays a remarkable performance, with 5 published papers that have accumulated 2045 citations in total and a H index of 18. This high volume of citations, despite only having a moderate number of publications, suggests that his research is of high relevance and has had a significant impact on the scientific community.

On the other hand, Tiwari GN, based in India, stands out as the most influential author in this group, with only 4 published papers, but a total of 19,068 citations and an H-index of 72, which positions him as a global reference in the application of renewable energies to protected agriculture and other related topics. This contrast in impact among authors suggests that, despite the European predominance, researchers in emerging countries such as India are also generating significant contributions that are widely recognized in the field.

It is important to note that Sonneveld PJ focuses his work on the development and evaluation of advanced solar technologies for application in built and agricultural environments. His research includes feasibility studies on the application of concentrated solar power (CPV) systems to greenhouses and conceptual designs for climate control in greenhouses using concentrated solar energy. Additionally, he investigates the integration of near-infrared (NIR) concentrators in greenhouses and explores light-trapping methods to enhance the efficiency of thin-film solar cells. On the other hand, Swinkels GLAM focuses on improving greenhouse efficiency, particularly in light transmission and energy conserva-

tion settings, through innovations such as ray-tracing models and diffuser covers. He has also contributed to the development of electricity-producing greenhouses and automated disease detection, supporting sustainability and productivity in protected agriculture. The author Bot GPA, meanwhile, has developed a comprehensive approach to greenhouse climate control, exploring topics such as energy balance and transport phenomena in the controlled environment of a greenhouse. In his most recent work, *Greenhouse Climate Control: An Integrated Approach*, he delves into the physical principles of greenhouse climates and methodologies used to optimize crop growth under closed conditions, highlighting how precise climate control can influence agricultural efficiency and productivity. Additionally, Bot GPA has collaborated in research on the integration of CPV (concentrated photovoltaic) systems in greenhouses, such as the use of NIR reflective lamellae in CPV systems, allowing for electricity generation by concentrating sunlight without compromising the light transmission needed for plant growth. This high-tech approach in greenhouses not only promotes sustainability but also optimizes energy performance, representing a key innovation in protected agriculture.

Table 1. Authors with the highest number of publications.

Author	Number of Documents	Citations	Total Citations	H-Index	Afiliation	Country
Sonneveld PJ.	9	274	499	9	Professor—Hogeschool van Arnhem en Nijmegen	The Netherlands
Swinkels GLAM	9	296	597	10	Researcher—Wageningen University & Research	The Netherlands
Bot GPA	7	275	3729	31	Independent Researcher	The Netherlands
Friman-Peretz M	6	117	121	5	Reseracher—Agricultural Research Organization of Israel	Israel
Van Tuijl BAJ	5	22	1444	11	Researcher—Wageningen University & Research	The Netherlands
Marucci A	5	333	1092	20	Professor -Università degli Studi della Tuscia Viterbo.	Italy
Poncet C	5	303	2045	18	Reasearcher- Institut Sophia Agrobiotech—(ISA)	France
Tiwari GN.	4	228	19,068	72	Professor—BERS Public School (BPS)	India

Friman-Peretz M specializes in the integration of organic photovoltaic (OPV) modules in greenhouse environments, focusing on how these systems can enhance energy efficiency and climate control without negatively impacting crop growth. Through his studies, he has explored the electrical performance, durability, and spectral and thermal properties of OPV modules when used as greenhouse covers or shading elements. His research includes detailed comparisons of the microclimate, the temperature, and other environmental factors in greenhouses featuring integrated OPV modules with those of conventional shaded tunnels, demonstrating how these systems can regulate solar radiation and temperature while generating electricity. This line of work highlights the potential of OPV modules for agricultural applications, promoting sustainability and efficiency in protected crop production. Meanwhile, Van Tuijl BAJ has contributed to the development of robotic and sensor technologies applied to protected agriculture. His research includes the integration of wireless sensor networks to analyze climate heterogeneity in greenhouses, showcasing innovations in automation and the optimization of controlled environments to enhance the efficiency of agricultural production. Additionally, Marucci A has investigated the use of photovoltaic technologies in greenhouses, focusing on energy efficiency and the integration of semi-transparent photovoltaic films in Mediterranean environments. His studies analyze internal shading, clear sky conditions, and the limits and prospects of these covers in greenhouses, proposing sustainable solutions that improve energy efficiency while optimizing growing conditions.

Finally, Poncet C focuses on the study of photovoltaic greenhouses, examining in particular how these panels affect the microclimate and tomato production in Canarian greenhouses. His research includes performance assessments in relation to seasons, shading levels in north–south-oriented greenhouses, and the distribution of solar radiation in various types of commercial photovoltaic greenhouses in Europe. These studies provide valuable insights into the optimization of solar energy use in protected agriculture. Similarly, Tiwari GN has conducted extensive research on greenhouse systems integrated with photovoltaic technology and heat exchange methods tailored to hot and dry climates. His studies cover topics such as the design of greenhouses with photovoltaic thermal systems and evacuated tubes for heat collection and the integration of passive and active solar systems into agricultural structures and biogas generators. Additionally, he has evaluated the performance of photovoltaic collectors combined with solar stills, optimizing energy efficiency and sustainability in agricultural production and water treatment.

On the other hand, Figure 2 shows a co-authorship graph, which reveals the existence of three main clusters that group authors according to their collaborations in this field of knowledge. Each cluster is differentiated by color, where the red cluster includes Bot GPA, Sonneveld PJ, Janssen HJJ and Campen J; the green cluster is centered on Swinkels GLAM together with Dieleman JA and Hemming S; and the blue cluster is organized around Van Tuijl BAJ. The graph reveals that there are a total of 22 links between the different clusters, with a total link strength of 66. A link represents the existence of joint publications between two authors, indicating that they have worked together on a project or article [45]. Link strength quantifies the intensity of collaboration: the higher the value, the higher the frequency of co-authored publications and thus the closer the collaboration between the authors [42]. In this context, the 22 links indicate an interconnected network where the groups are not isolated but interact actively through certain authors who serve as bridges.

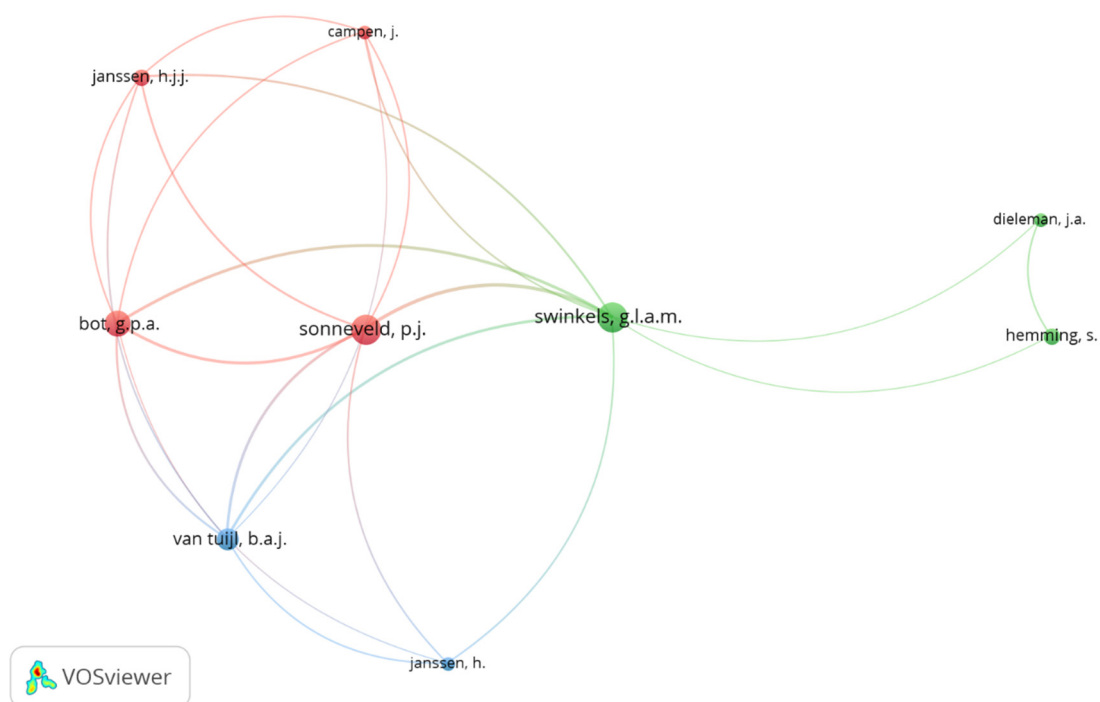


Figure 2. The main network of co-authorship.

Analyzing the link strength by author, the node featuring Swinkels GLAM is the most prominent, with 8 links and a strength of 28, suggesting that he is a key author in terms of connecting clusters and facilitating knowledge transfer between groups. Sonneveld PJ presents 6 links and a strength of 26, with the graph reflecting the important role of his cluster in internal cohesion and his collaborations with the green cluster. Bot GPA also

has 6 links and a strength of 20, indicating a moderate level of collaboration, even if it is probably concentrated in highly relevant work and in specific areas. These metrics reinforce the importance of these authors. This is not only due to their number of publications, but also their ability to act as leaders of their clusters and facilitators of scientific cooperation.

3.3. Institutions with the Highest Scientific Production

As for the institutions that have generated the largest number of papers in the field of research on solar applications in protected agriculture, it was found that Wageningen University & Research (<https://www.wur.nl/en.htm>) leads with 13 publications. This is not surprising, as this university is globally recognized as a reference in the field of agriculture and sustainability, with a particular focus on the integration of advanced technologies for efficient agricultural production and the mitigation of environmental impacts under canopy conditions. Wageningen's dominance suggests its leadership in the research and development of innovative methodologies and applications involving solar energy for greenhouse crop optimization, with its research and business development unit mainly focused on greenhouse agriculture in different regions worldwide (<https://www.wur.nl/en/research-results/research-institutes/plant-research/business-units/greenhouse-horticulture.htm>).

In second place, King Saud University (<https://ksu.edu.sa/en>), with 5 papers, is positioned as an important player in the Middle East, where the implementation of solar technologies is strategic due to climatic conditions and the abundance of solar radiation. Its contribution could be focused on adapting and validating solar technologies for use in protected agriculture systems in arid environments, addressing challenges such as temperature control and water management in greenhouses.

Finally, the group formed of NC State University (<https://www.ncsu.edu/>), the Indian Institute of Technology Delhi (Home Page: IIT Delhi), and the Ministry of Education of the People's Republic of China (<http://en.moe.gov.cn/>), with 4, 4, and 3 papers, respectively, shows the importance of research on the subject in different geographical contexts. While universities in the United States and India may be exploring solar applications in relation to sustainability and efficient agricultural production, the participation of a Chinese government entity reflects an institutional interest in promoting the development and implementation of these technologies in a country with high agricultural needs and strong environmental sustainability policies. Taken together, these data demonstrate the global interest in the use of solar energy in protected agriculture, with leading research centers contributing to the expansion of knowledge and the development of solutions that can be adapted to different contexts.

3.4. Number of Publications and Co-Authorship by Country

The analysis of the distribution of papers by country in terms of research on solar energy applications in protected agriculture shows the clear concentration of contributions in certain countries, with the predominance of the United States (21), India (18 papers), and the Netherlands (16). These three countries lead the development of knowledge and technologies, standing out for their high levels of scientific production in this field. The presence of India in the first place may be due to the growing importance of solar energy in agriculture in regions with high solar radiation and the demand for sustainable solutions to mitigate the impact of climate change on agricultural production [46]. The Netherlands and the United States, on the other hand, are characterized by their leadership in greenhouse technology development and innovation, with a strong focus on the integration of renewable energy to improve the efficiency of these crop production systems [47].

The next category includes countries such as China (15 papers), Japan (8 papers) and Turkey (8 papers), which are also developing relevant research capabilities, possibly driven by increased investment in renewable energy and the need to adapt their agricultural systems to new climatic conditions [48]. In the case of countries such as Saudi Arabia (7), Iran (7), and Italy (6), their contributions reflect a particular interest in solar technologies

applied in Mediterranean, arid, and semi-arid climates, where efficient water and energy management is crucial [49]. The remaining countries (with 1 to 4 papers) represent sporadic contributions that could indicate emerging efforts in the integration of solar energy with protected agriculture, suggesting potential areas for future collaboration to strengthen their research capabilities in this area. Overall, the distribution of papers reflects a core of countries with high scientific productivity and a wide range of nations that are making inroads in this area, opening opportunities to expand international cooperation and foster the development of solutions that are adapted to different agroclimatic contexts.

Co-authorship analysis (Figure 3) by country allows us to observe the collaborative relationships between countries in terms of scientific publications. In this type of analysis, key elements include nodes, links, and link strength. Each node in the graph represents a country, and its size corresponds to the number of papers produced in the research area. In this context, the United States stands out as the country with the largest number of papers, as mentioned above, followed by India, the Netherlands, and China. Other countries, such as Japan, Germany, Italy, Saudi Arabia, France, and Turkey, also contribute to the scientific corpus in this area, although with a smaller volume of scientific production.

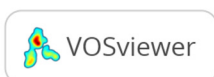
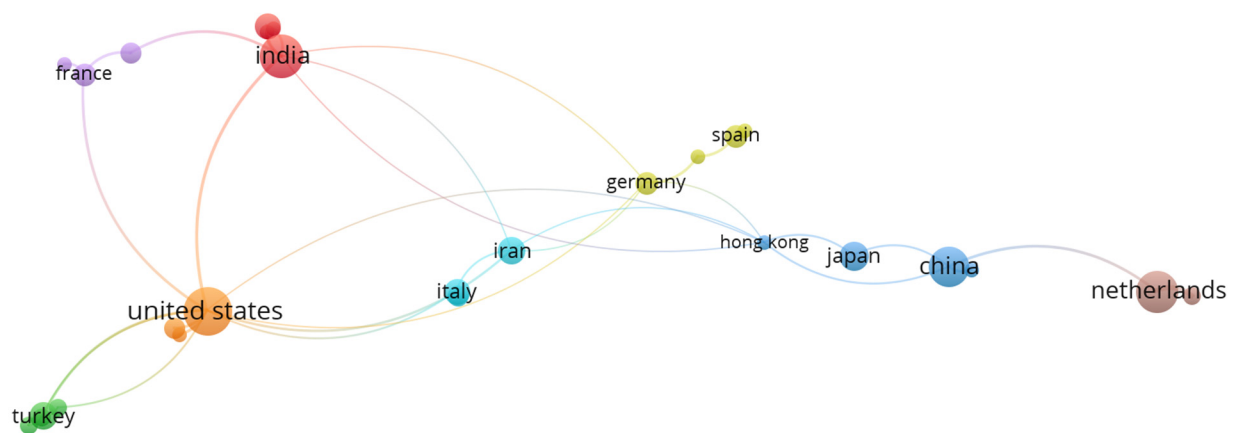


Figure 3. Co-authorship network by country.

The links between the nodes indicate co-authorship relationships between countries, reflecting collaboration in the production of scientific publications [4]. The United States shows 11 links, denoting its extensive collaborative network with other countries. India follows with 8 links, reflecting active and collaborative participation in the field. The Netherlands and China have 2 and 4 links, respectively, suggesting a smaller number of international partnerships, although these countries are significant in terms of scientific output. Japan has 1 link, while Germany has 5, Italy has 3, Saudi Arabia has 1, France has 3, and Turkey has 3, indicating varying degrees of connection in co-authorship networks.

Linkage strength refers to the intensity of collaboration between the connected countries, and a higher value suggests more robust collaboration [4,50]. The United States has the highest link strength, with a value of 8, followed by India, with a value of 6, indicating a strong and frequent connection in their scientific collaborations. The Netherlands and China, with a link strength of 4 and 3, respectively, also show a moderate collaborative relationship. Germany and France have a link strength of 2 and 3, respectively, while Japan, Saudi Arabia, and Italy show a lower link strength (1 or 2), indicating less intense collaboration.

In conclusion, the graph reveals that the United States and India lead in terms of scientific production and international collaboration related to the application of solar energy to protected agriculture, which positions them as key players in this field of research. The Netherlands and China also show outstanding contributions, although with less dense collaboration networks. This analysis of nodes, links, and linkage strength allows us to identify collaborative dynamics and international alliances, providing insight into scientific interactions and opportunities for collaboration to strengthen research in the application of solar technologies to protected agriculture.

3.5. Favorite Sources of Publication by the Scientific Community

The analysis of the scientific production related to solar energy applications in protected agriculture in the main journals shows that the highest number of publications is found in *Acta Horticulturae* (17 papers), a horticulture journal with an H-index of 71 which is located in Q4 (Table 2). Its specialization in agricultural and horticultural topics suggests that many of the studies focus on the implementation of solar technologies in protected cropping systems, such as greenhouses, in order to improve production efficiency. The fact that it is published in *Acta Horticulturae* also suggests a high level of relevance for the agricultural sector and the scientific community dedicated to sustainable food production.

Table 2. Top 10 publication sources selected by the authors.

Journal	No. Documents	SJR Ranking	H-Index	Country
<i>Acta Horticulturae</i>	17	Q4	71	Belgium
<i>Solar Energy</i>	10	Q1	224	United Kingdom
<i>Geliotekhnika</i>	6	Q4 (2008)	7	Uzbekistan
<i>Renewable and Sustainable Energy Reviews</i>	6	Q1	421	United Kingdom
<i>Energy Conversion and Management</i>	6	Q1	250	United Kingdom
<i>Applied Energy</i>	5	Q1	292	United Kingdom
<i>Aip Conference Proceedings</i>	2	NA	83	United States
<i>Applied Thermal Engineering</i>	2	Q1	206	United Kingdom
<i>Desalination</i>	2	Q1	231	Netherlands
<i>Energy</i>	2	Q1	251	United Kingdom

On the other hand, high-impact journals in the field of energy, such as *Solar Energy*, *Renewable and Sustainable Energy Reviews*, and *Energy Conversion and Management*, which belong to Q1, stand out for their focus on technological innovation and the development of sustainable energy systems. *Solar Energy* has 10 papers and an H-index of 224, which highlights its position as one of the main sources for the publication of relevant research on the use of solar energy in greenhouses. Similarly, *Renewable and Sustainable Energy Reviews* (6 papers and an H-index of 421) presents a comprehensive focus on renewable energies, positioning itself as a key platform for the dissemination of cutting-edge research. The presence of these journals reflects the interdisciplinarity of the subject and the importance of combining agricultural knowledge with advances in renewable energies.

At a lower level of production, but also relevant, we find journals such as *Desalination* and *Applied Thermal Engineering*, which have 2 papers each and belong to Q1, suggesting an orientation towards specific applications, such as the use of solar energy for desalination and the thermal optimization of agricultural systems. Finally, journals such as *Geliotekhnika* from Uzbekistan (Q4) represent publication niches in emerging regions, which may indicate a growing local interest in developing solutions adapted to the climatic conditions.

Figure 4 shows an inter-journal citation network graph, which reflects the collaborative structures of and interconnectivity between the main scientific sources that publish on solar energy and its application in protected agriculture. The nodes represent the journals and the links indicate the citations that exist between them, reflecting the transfer of knowledge and the relative importance of each journal in the development of the topic [51]. Link strength measures the intensity of citations: the greater the strength, the greater the frequency

with which one journal cites the other, suggesting a stronger relationship of influence between the articles [33,52]. *Solar Energy* and *Renewable and Sustainable Energy Reviews* are the journals with the highest connectivity in the network, with 3 links each. *Solar Energy* has a link strength of 5, while *Renewable and Sustainable Energy Reviews* has a total strength of 6, suggesting that the latter has a greater influence on joint publications and knowledge transfer between different journals. Their central positions and links to *Energy Conversion and Management* and *Applied Energy* indicate that they act as reference platforms for high-impact publications in the field of solar energy.

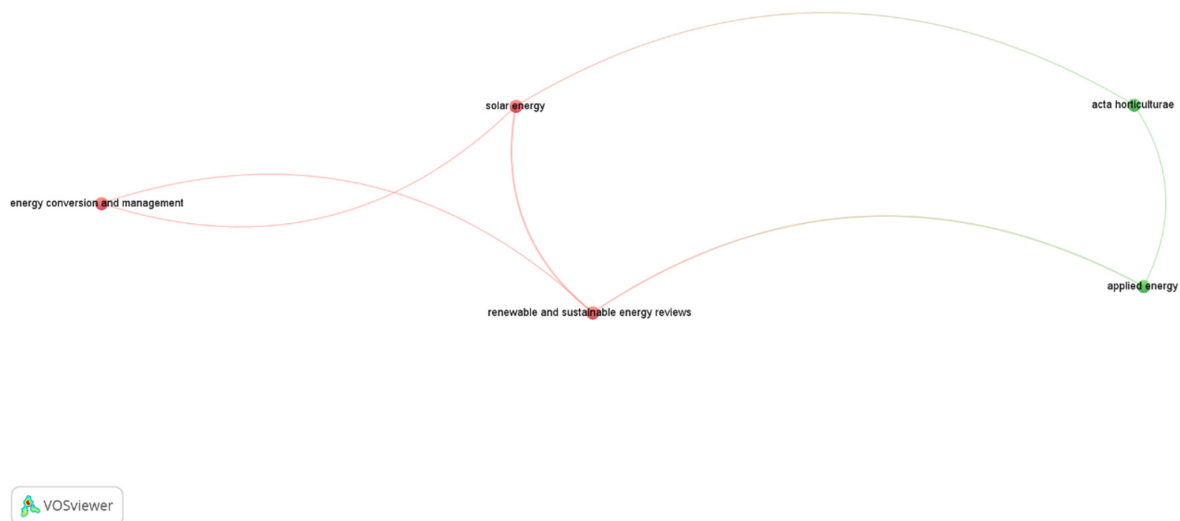


Figure 4. Citation network between publication sources.

On the other hand, *Applied Energy*, with 2 links and a strength of 3, and *Energy Conversion and Management*, with 2 links and a strength of 2, show a moderate degree of influence in the network. Although their numbers of links are lower, their presence in the network suggests that they are journals in which more applied and specific studies are published, which could be related to the evaluation of energy conversion and management technologies in the context of protected agriculture. These journals are positioned as points of liaison between technological developments and their adaptation to practical applications in agricultural energy systems. The connections with more influential journals suggest that the articles published in them benefit from a constant flow of knowledge and the transfer of experimental techniques, consolidating their role in the process of the technological maturation of research.

Finally, *Acta Horticulturae* has 2 links and a strength of 2, reflecting a specialized role in the network. It is focused on the dissemination of research that is more oriented to agricultural production and the implementation of technologies in greenhouse systems. Although its level of interconnectivity is lower compared to energy journals, its presence underscores the relevance of its content to the agricultural community, acting as a link between technological development and direct application in the horticultural sector. Overall, the citation network shows a strong interrelationship between high-visibility journals in the energy field, such as *Solar Energy* and *Renewable and Sustainable Energy Reviews*, and publications focusing on specific applications, critical and systematic reviews, and case studies, suggesting that the application of solar energy research to protected agriculture is interconnected with other developments in renewable energy, reflecting an interdisciplinary field that combines both technological innovation and practical implementation in agricultural production.

3.6. Recently Published Articles

The analysis of recently published articles reveals a growing trend towards the integration of renewable technologies and smart systems to optimize climate control and

energy efficiency in greenhouses. The use of IoT sensors and microcontrollers such as the Arduino and Raspberry Pi has enabled the development of more accessible and accurate monitoring and control systems. For example, an Arduino-based automated greenhouse proved to be able to regulate temperature through fans and collect humidity data with high accuracy, mitigating land and labor requirement issues for small farmers and gardeners, providing adequate data for agricultural researchers, and improving crop yields in a controlled environment [53]. Similarly, a monitoring system using Raspberry Pi allowed for the real-time measurement and control of electrical and environmental parameters, standing out for its ability to operate remotely, which is crucial in rural areas. The main results show that the system is efficient in increasing the sustainability and operational performance of greenhouses by optimizing energy consumption and maintaining optimal conditions for crop development. These findings highlight the potential of the incorporation of smart technologies into agriculture to achieve energy independence and maximize production [47]. These technologies are geared towards achieving the energy autonomy of greenhouses, especially when combined with solar energy systems, as described in both articles.

Regarding the application of renewable energies in greenhouses, novel approaches are presented for the use of hybrid systems that combine solar thermal and photovoltaic energy to maximize energy efficiency. For example, a hybrid solar dryer for tomato processors achieved a thermal efficiency of 72.21% and a drying efficiency of 56.48%, providing 84.28% of the total heat output generated during the experiment [54]. On the other hand, under a multi-objective optimization framework applied to a solar system with heat storage, and using a 1065 m² solar collector, a boiler, and a thermal storage system to meet the heating demands of greenhouses, an 89.5% reduction in CO₂ emissions was achieved compared to the system with the lowest cost [55]. These results demonstrate that the integration of solar technologies with energy storage can be highly efficient in terms of emissions reduction and energy harvesting, providing sustainable options for large-scale agriculture.

Research in advanced solar energy systems has also explored innovative applications, such as the use of updraft solar towers and agrivoltaic systems. The work developed by Marzouk [56] details a numerical study on tower solar power plants, with results showing an output between 0.93 and 2.28 kWhm⁻² per year depending on the geographical location. Although these plants are not competitive with traditional photovoltaic systems, their use is suggested in hybrid projects to generate clean electricity and provide energy in cultivation areas under a large-scale greenhouse environment. On the other hand, Song et al. [57] highlights the potential of organic photovoltaics (OPVs) in agricultural systems on account of their flexibility and selective absorption spectra, factors which allow for a more effective combination in order to avoid limiting crop photosynthesis. The implementation of OPVs could increase the energy efficiency of greenhouses, reduce dependence on the conventional electrical grid, and optimize the use of sunlight for crop growth and development.

In addition, there is interest in improving the efficiency of heat collection and storage in solar greenhouses. In this regard, there are works that highlight new greenhouse designs, with water heat accumulators installed under the northern roof, that achieve a higher energy collection efficiency and an increase of more than 12% in heat release, which translates into a greater use of solar radiation compared to conventional designs [48]. Finally, the focus on the implementation of intelligent systems for the adaptive control of energy and climatic conditions in greenhouses is a relevant trend.

The work developed by Solis et al. [58] presents an adaptive control system that uses artificial intelligence algorithms to optimize lighting based on renewable energy sources, automatically adjusting the light intensity based on local solar energy production. This system makes it possible to reduce energy consumption by efficiently adapting to fluctuations in solar irradiance. This approach is complementary to the recommendations of the work performed by Dharunjayavinayak et al. [59], which highlights the importance of artificial intelligence in overcoming the limitations of conventional systems, improving accuracy and autonomy in greenhouse management. The combination of these technologies represents the future of smart agriculture, with the ability to integrate multiple energy

sources and optimize processes in real time ensuring the sustainability and efficiency of modern agricultural systems.

The integration of advanced photovoltaic (PV) technologies into greenhouses shows promise in terms of both energy generation and agricultural productivity. For instance, the study conducted by Chatterjee et al. [60] highlights the potential of green-light-wavelength-selective organic solar cells (GLWS-OSCs), which convert green light into electricity while allowing red and blue light, essential for photosynthesis, to reach crops. By using a cost-effective donor–acceptor combination, these organic solar cells maintain high energy conversion efficiency and demonstrate prolonged stability, showing minimal interference with photosynthesis and thereby supporting crop growth, as evidenced by tomato cultivation tests. These findings emphasize that GLWS-OSC technology is a viable agrovoltaic solution for greenhouses, optimizing solar energy use while maintaining crop productivity.

In terms of optimizing greenhouse environments with PV coverage, the work presented by Li et al. [61] introduces a model used to simulate radiative heat gain and the impact of different PV coverage ratios on the internal microclimate of a greenhouse. The study found that, with each 12.5% increase in PV coverage, internal irradiation was modestly decreased depending on the season, while indoor temperatures were also slightly reduced. The optimal PV coverage rates varied by season (62.5% for equinoxes, 50% for the summer solstice, and 25% for winter), and these conditions maximized both energy generation and favorable conditions for crop growth. This research demonstrates how customized PV configurations can balance energy production with ideal microclimatic conditions in greenhouses, enhancing seasonal adaptability.

It is also important to mention that the concept of agrivoltaics extends beyond greenhouses to encompass various agricultural settings but faces challenges, such as economic viability, wind loads, and potential interference with agricultural activities. The study conducted by Zahrawi and Aly [62] addresses these issues, underscoring the importance of wind load management in agrivoltaic systems in order to ensure structural stability. This study also highlights a critical knowledge gap in aerodynamic load mitigation, emphasizing the need for research on damping, mass increase, and optimal positioning to enhance the viability of agrivoltaics. This underscores the necessity of finding solutions that allow for the implementation of agrivoltaic systems without compromising agricultural productivity, particularly under diverse environmental conditions.

Finally, solar irradiance prediction is vital for PV systems installed in greenhouses to function efficiently under fluctuating light conditions. Zhu et al. [63] conducted work on solar irradiance prediction, with variable time lengths and multiple parameters in full climate conditions based on photovoltaic greenhouse technology, presenting predictive models (e.g., Transformer, Pyraformer, TimesNet) to accurately forecast irradiance and incorporating parameters such as daily sunlight duration, instant irradiance, and cumulative irradiance. Among these, the Transformer model performed best across various time intervals, while the Pyraformer and TimesNet models showed seasonal variation in accuracy. These models enable more precise irradiance management in PV-integrated greenhouses, supporting effective energy use and climate control. This predictive approach helps to refine greenhouse management, addressing the need for models that adapt to specific climatic conditions and solar dynamics.

3.7. Top Most Cited Articles

The analysis of the most cited articles reveals the need to optimize the use of renewable energy resources in agricultural systems to promote sustainable development (Table 2). The exergy analysis of renewable energy resources (RERs) proves to be an effective quantitative approach with which to evaluate the performance of different energy technologies applied in agriculture, as mentioned in the energy evaluation section of Article 1. The findings of this study mention that the energy efficiencies of a solar collector, a photovoltaic system, and a hybrid solar collector were 4.4%, 11.2%, and 13.3%, respectively. In terms of power quality, the hybrid solar collector was very efficient, further highlighting the importance

of developing technological solutions that maximize the use of solar energy. In addition, Article 2 discusses how retrofitting greenhouses with thermal storage technologies and climate control systems based on renewable energy can achieve energy savings of up to 80%, with a payback period of 4 to 8 years. This convergence of emerging technologies with advanced analytical methodologies represents a key trend towards the implementation of energy-efficient systems in protected agriculture.

In terms of technology integration, photovoltaic/thermal (PV/T) systems play a central role in reducing energy consumption in greenhouses. Article 3 validates a thermal model for a greenhouse in India, achieving an exergy efficiency of 4%, while the predicted and measured internal temperatures show a significant correlation (correlation coefficient between 0.95 and 0.97), underlining the accuracy of the model under specific climatic conditions. Article 5 presents an advanced greenhouse design with linear Fresnel lenses and a CPV system that concentrates direct solar radiation, achieving a combined efficiency of 67% and reducing the required cooling capacity by a factor of 4 during the summer. This system generated 38 Wm^{-2} of electrical energy and 170 Wm^{-2} of thermal energy under experimental conditions, highlighting the potential of these configurations for application in regions with high levels of solar radiation. Both articles highlight how the use of combined technologies not only improves energy generation, but also the stability of the microclimate in greenhouses.

The use of solar technologies in greenhouses to optimize climate control and crop production efficiency has been extensively studied in the context of different regions. Article 4 evaluates the use of solar systems for greenhouse heating and cooling, showing that the implementation of these systems in rural areas can reduce energy consumption by 20% compared to conventional methods. Similarly, Article 13 examines a greenhouse that combines photovoltaic modules and thermal collectors, achieving the annual production of 20 kWhm^{-2} of electrical energy and 160 kWhm^{-2} of thermal energy. The incorporation of near-infrared radiation (NIR) reflection technology significantly improved the internal climatic conditions of the greenhouse, reducing the demand for external heating. In addition, the authors mention that, with future improvements in the film, 31 kWhm^{-2} of electrical energy and 270 kWhm^{-2} of thermal energy could be generated, which would make the greenhouse self-sufficient and not dependent on fossil fuels. These results highlight the relevance of adapting technologies to local conditions in order to maximize efficiency and minimize the environmental impact of agricultural operations.

Likewise, the implementation of modern solar greenhouses and the use of thermal storage technologies in energy-constrained regions represents a promising trend. In Article 11, China's progress in the development of solar greenhouses with thermal storage capacity is discussed. In this country, a viable economic payback period of less than nine years has been achieved. This progress is complemented by the analysis in Article 12, which highlights how retrofitting greenhouses in Europe could reduce energy consumption by 70% by using solar collectors and artificial intelligence technologies to optimize climate control. Both studies demonstrate that the use of integrated solar energy and thermal storage systems not only optimizes energy use, but also contributes to mitigating the environmental impact of agricultural activities, providing a sustainable approach to protected agriculture in different climatic conditions and geographical contexts. It is important to mention that the effects of photovoltaic shading and microclimate on crop growth have also been studied. Various studies have assessed the impact of shading, caused by photovoltaic panels, on crop growth within greenhouses. In the case of photovoltaic greenhouses (PVGs) with 10% photovoltaic coverage, it has been observed that there is no significant effect on the agronomic parameters of tomatoes, such as height, stem diameter, and yield, or on the overall microclimate of the greenhouse, as mentioned in Article 9. Similarly, in Article 7, the creation of building-integrated photovoltaic (BIPV) modules on a greenhouse roof—covering 20% of the area with a 30° tilt—showed that, despite reducing solar radiation by 35–40%, crop growth was not significantly affected ($p < 0.05$) and air temperature was reduced by 1°C to 3°C on clear days, with no effects on relative humidity. These findings suggest that the use

of photovoltaic panels with moderate coverage allows for the coexistence of agricultural and energy production without impacting crop development. Likewise, Articles 10 and 15 mention that, with 78% shading, photovoltaic generation power reached its maximum, but agricultural production was compromised, suggesting the need for supplemental LED lighting in scenarios with high PV R values to avoid productivity losses.

Similarly, Article 10 explores the optimization of the photovoltaic coverage ratio (PV R) and light distribution, which are crucial parameters in terms of maintaining a balance between energy generation and crop lighting needs in photovoltaic greenhouses. For crops with a high light demand, such as tomatoes and cucumbers, a PV R of up to 25% allows for an insignificant or limited reduction in yield, while medium-light crops can grow in PVGs with a PV R of up to 60% without compromising productivity. On the other hand, low-light-demand floriculture species, such as poinsettia, adapt to greenhouses with a PV R of up to 100%. Similarly, in Article 15, it is mentioned that a north–south greenhouse orientation, combined with a checkerboard pattern, increases the average solar radiation in the greenhouse area by up to 24% and improves the light distribution uniformity. These adjustments are fundamental for the design of photovoltaic greenhouses, aimed at maximizing agricultural productivity across various crop types.

Finally, regarding energy efficiency and sustainability in photovoltaic greenhouses, studies also highlight the energy efficiency of photovoltaic greenhouses and their sustainability in terms of energy generation and consumption (Table 3). A BIPV system mounted on a greenhouse generated 637 kWh annually, meeting most of the energy demands of environmental control systems, and had a payback period of 9 years, as mentioned in Article 7. Similarly, Article 12 presents a prototype dynamic photovoltaic greenhouse that allows panel rotation to adjust shading, demonstrating that the energy production and microclimate remained within optimal ranges for commercial crops, with sufficient solar radiation values for normal agricultural operations during most of the experiment.

Table 3. The most cited articles.

Document	Title	Number of Citations	Reference	Journal
1	A key review on exergetic analysis and assessment of renewable energy resources for a sustainable future.	771	[64]	<i>Renewable and Sustainable Energy Reviews</i>
2	Renewable and sustainable energy saving strategies for greenhouse systems: A comprehensive review.	257	[65]	<i>Renewable and Sustainable Energy Reviews</i>
3	Energy and exergy analysis of photovoltaic/thermal integrated with a solar greenhouse.	185	[66]	<i>Energy and Buildings</i>
4	The application of solar technologies for sustainable development of agricultural sector.	140	[67]	<i>Renewable and Sustainable Energy Reviews</i>
5	Performance of a concentrated photovoltaic energy system with static linear Fresnel lenses.	140	[68]	<i>Solar Energy</i>
6	Thermodynamic and economic considerations in solar desalination.	134	[69]	<i>Desalination</i>
7	The integration of semi-transparent photovoltaics on greenhouse roof for energy and plant production.	130	[70]	<i>Renewable Energy</i>
8	Energy sustainable greenhouse crop cultivation using photovoltaic technologies.	127	[71]	<i>Renewable and Sustainable Energy Reviews</i>
9	The effect of photovoltaic panels on the microclimate and on the tomato production under photovoltaic canarian greenhouses.	110	[72]	<i>Solar Energy</i>
10	Agricultural sustainability estimation of the European photovoltaic greenhouses.	109	[73]	<i>European Journal of Agronomy</i>
11	Integration of solar technology to modern greenhouse in China: Current status, challenges and prospect.	108	[74]	<i>Renewable and Sustainable Energy Reviews</i>
12	Solar thermal simulation and applications in greenhouse.	102	[75]	<i>Information Processing in Agriculture</i>
13	Performance results of a solar greenhouse combining electrical and thermal energy production.	96	[76]	<i>Biosystems Engineering</i>
14	Dynamic photovoltaic greenhouse: Energy efficiency in clear sky conditions.	92	[77]	<i>Applied Energy</i>
15	Assessment and comparison of the solar radiation distribution inside the main commercial photovoltaic greenhouse types in Europe.	90	[78]	<i>Renewable and Sustainable Energy Reviews</i>
16	Solar energy utilization by a greenhouse: General relations.	73	[79]	<i>Renewable Energy</i>

3.8. Solar Technology Applications Dedicated to Tomato Crop Production and Other Crops of Interest

Tomato (*Solanum lycopersicum*) cultivation occupies a prominent place worldwide, with more than 5 million hectares planted and the production of more than 180 million tons in 2022, according to recent reports [80]. However, within the supply chain, greenhouse-grown tomatoes are considered high-value crops that play an important role in world agriculture due to their ability to provide a stable supply throughout the year [81]. Therefore, its high demand and nutritional value make it a priority target for the implementation of advanced greenhouse technologies and sustainable management practices.

Accordingly, it should be mentioned that the first studies were developed 4 decades ago, exploring a hybrid approach to agricultural production using multifunctional solar greenhouse systems that combine large solar collectors and transparent structures for curing, drying, and seedling production. It was demonstrated that, during the production of tomato and other crop seedlings, this system achieved fuel savings of 47–54% compared to conventional methods. These systems were subsequently converted into greenhouses for the automated production of flowers, cucumbers, and tomatoes, demonstrating that seedlings grown in these environments adapted better to transplantation and achieved superior growth compared to traditional systems [82].

Subsequently, studies focused on the use of thermal models to evaluate the energy performance of conventional greenhouses. The authors of [79] describe a simulation model, based on superposition and ray-tracing theory, used to estimate the amounts of solar energy absorbed and lost by the components of an experimental greenhouse. However, this model has limitations in that it does not include the impact of seasonal variations or thermal storage systems, reducing its applicability to more complex scenarios. This initial approach established the basis for further studies, but was not sufficient to address the need for energy savings and microclimate optimization.

Over time, closed greenhouse systems have emerged that integrate advanced climate control technologies in order to reuse energy and improve efficiency. In [83], the authors detail the development of the “GeslotenKas” closed greenhouse concept in the Netherlands, where a 20% increase in tomato yields was achieved compared to conventional greenhouses. In this system, solar energy is stored and reused for heating, reducing dependence on fossil fuels and increasing the stability of the growing environment [84]. Under this design, tomato production proved to be cost-effective under arid climatic conditions but maintained high energy efficiency. Despite these advances, enclosed greenhouses face challenges such as moisture management and CO₂ accumulation, and further development of ventilation and latent heat storage strategies is required to maximize their potential.

In the area of renewable energy system integration, the ZINEG program in Germany, which aimed to reduce fossil fuel consumption by 81% during tomato production using solar thermal collector systems and heat storage, achieved a seasonal energy efficiency ratio (SEER) of 5.1 and a seasonal heating performance factor (HSPF) of 4.4. During the production season in 2011, a seasonal energy efficiency ratio (SEER) of 5.1 and a heating seasonal performance factor (HSPF) of 4.4 were achieved by collecting 1.76 GJm^{−2} of solar energy in an insulated rainwater tank. Approximately 0.53 GJm^{−2} of the stored heat was reused, reducing primary energy consumption to 147.6 MJm^{−2} compared to the 767.1 MJm^{−2} used by a conventional greenhouse [85]. These results underscore the feasibility of using hybrid systems that combine solar energy with thermal storage to significantly reduce the use of non-renewable fuels, although detailed economic studies are required to assess their cost-effectiveness on a large scale.

The analysis of advanced technologies for tomato production in greenhouses has evolved towards approaches that combine the optimization of structural design and the efficient use of solar energy. The work developed by Dieleman et al. [86] focuses on innovations in Dutch horticulture, where strategies such as the use of 3D ray tracing models have been implemented to quantify the effect of greenhouse geometry and canopy properties on light transmission during low-solar-elevation months. This technique allowed us to increase natural light capture by 10–20% during winter, which is crucial for maintaining

tomato growth under low-radiation conditions. In addition, the use of wireless sensors to measure temperature and humidity distribution, together with the use of web-based decision support models, has enabled the development of the “mobile climate measurement box” and “botrytis alert”, strategies that have proven to be effective in reducing disease risk and saving energy by 10%. These innovations focus on maximizing the use of free sunlight and optimizing greenhouse climate management, offering low-energy impact solutions in order to maintain crop productivity throughout the year. Another relevant study is the one developed by Ghaffarpour et al. [87], who evaluated an east–west-oriented greenhouse equipped with PV using a mathematical model, integrating energy, growth, and PV models to determine heating and cooling requirements, tomato production, and electricity generation. Near Tehran, a 25° south-angled roof with 25% PV coverage reduced energy consumption by 15.06% per kilogram of tomatoes, achieving 15.52 tons of tomatoes and using 46.4 MWh of electricity in nine months. The optimal arrangement of the panels on the roof was an asymmetrical checkerboard pattern, offering a valuable option for analyzing the benefits and limitations of PV greenhouses.

Finally, recent research has explored the implementation of organic solar cells (OSCs) in greenhouses to generate electrical energy without compromising crop productivity. There is an energy optimization and plant growth model that investigates OSC greenhouses in 25 different climates, considering up to 64 active layers of OSCs. The results show that the use of OSCs allows us to maintain tomato yields in various climates and improve the net value of the system compared to conventional greenhouses. In certain locations, the use of OSCs achieved up to 15% improvement in the economic value of the greenhouse, while generating enough energy to cover supplemental lighting needs [88]. A study conducted in the southeast of Spain demonstrated that flexible solar panels mounted on greenhouse roofs could generate electricity without significantly impacting tomato yield or marketability, even though slight differences were observed in fruit size and color compared to control setups without panels. Notably, solar panels covering 9.8% of the roof area maintained tomato production levels while offering opportunities for energy generation, providing additional income streams for growers without altering the commercial classification of the produce [89]. Additionally, innovative methodologies, such as the extended PAR-based photosynthesis (EPBP) approach in photovoltaic greenhouses (PVGHs), demonstrated substantial improvements in tomato yields. By leveraging LED technologies to extend photosynthesis during dawn and dusk, this method increased crop productivity by 51.29% compared to conventional PVGH systems, enhancing both yield quality and economic returns, with a return on investment (ROI) exceeding 14% [90]. These advances represent a paradigm shift towards the implementation of energy-autonomous greenhouses, with a focus on maximizing the use of clean and sustainable energy.

Regarding crops other than tomatoes, a study conducted in Israel evaluated three types of semi-transparent photovoltaic panels installed in a polyethylene greenhouse where cucumbers were cultivated. The results indicated that the use of glass-encapsulated silicon panels not only did not reduce crop yield but also improved plant growth and fruit quality compared to a control greenhouse without panels. This type of panel demonstrated higher energy efficiency under high-temperature and high-humidity conditions, suggesting that agrivoltaic technology is a viable alternative with which to optimize agricultural production while generating clean energy [91]. Similarly, studies on agrivoltaic systems reveal that the shading effect of photovoltaic panels can modify microclimatic conditions, such as soil temperature and incident radiation, without significantly affecting the growth of crops like lettuce, cucumbers, and wheat. Although minor differences were observed in the early growth stages of short-cycle crops, the systems maintained comparable productivity levels to conventional setups. Furthermore, innovative configurations, such as integrating vertical farming systems into closed agrivoltaic systems, increased land productivity by up to 13 times compared to traditional methods, demonstrating the potential of agrivoltaics to enhance agricultural sustainability [92,93].

In the case of green beans and Welsh onions, the use of photovoltaic greenhouses presented challenges related to shading intensity. Reduced light availability led to a decrease in fresh biomass and fruit size while prompting physiological adaptations, such as an increased specific leaf area and improved radiation use efficiency. These responses highlight the importance of panel arrangement, with intermittent shading patterns proving less detrimental to crop performance than continuous shading. The strategic optimization of photovoltaic coverage can help to achieve a balance between energy generation and crop yield, ensuring the economic viability of the system [94,95]. Moreover, photovoltaic greenhouses have shown potential to enhance the nutritional quality of certain crops. Studies on berries and baby leaf lettuce have demonstrated that moderate shading can increase concentrations of bioactive compounds, such as polyphenols, anthocyanins, and carotenoids, without compromising overall productivity. These findings, combined with the use of supplemental LED lighting, allow precise control over light quality, maximizing the synthesis of phytochemicals and improving the health benefits of harvested produce. This dual approach of optimizing crop quality and generating renewable energy underscores the role of photovoltaic greenhouses in sustainable agriculture [96,97].

On the other hand, when maximizing crop efficiency in agrivoltaic greenhouses, light control is a fundamental factor. A recent study investigated how materials used in photovoltaic modules, such as glass and transparent back sheets, can increase light diffusivity in intensive cropping systems. This increase in light diffusion allows for deeper penetration into the crop canopy, enhancing the photosynthesis rate and, consequently, crop yield [98]. Finally, microclimate control is another key aspect of crop productivity under agrivoltaic systems. In an experiment conducted in Egypt, the effects of two glazing materials, fiberglass and polyethylene, were compared in a cucumber greenhouse with a solar heating system. The results showed that the fiberglass greenhouse maintained a higher internal temperature compared to polyethylene, resulting in a 30.12% increase in cucumber production [99]. This study underscores the importance of selecting appropriate covering materials that promote heat retention and improve microclimatic conditions, thereby optimizing crop productivity in greenhouses equipped with solar technology.

3.9. Most Used Keywords and Keyword Co-Occurrence Map of Selected Scientific Publications

The word cloud shown in Figure 5 displays a synthesis of the predominant themes in the research on the use of solar energy in greenhouses, with a clear focus on renewable energy technologies and their application in agriculture. The term “greenhouses” occupies the most prominent position, with 87 occurrences, showing that most of the literature focuses on the implementation of greenhouses as a key solution in agricultural production. The second most mentioned word is “solar energy”, with 69 mentions, indicating that much of the research explores how to integrate solar energy sources to improve sustainability in greenhouses. These terms point to the growing interest in the convergence between agricultural and energy technologies as a response to environmental and economic challenges.

As for terms related to thermal energy, “heating” and “solar heating” make 22 appearances, highlighting the importance of thermal regulation in greenhouses. In agricultural contexts, greenhouses require precise environmental control to optimize crop growth, and the use of solar heating offers an efficient solution in terms of both cost and environmental impact. In addition, the term “solar power generation”, with 19 mentions, reflects a growing interest in the generation of clean energy within these systems, which not only improves operational efficiency, but also contributes to the energy self-sufficiency of greenhouses, a particularly relevant strategy in rural areas or areas with limited access to energy.

Other notable concepts, such as “energy utilization” and “heat storage”—with 20 and 15 mentions, respectively—underscore the attention researchers are paying to energy efficiency and resource management in greenhouses. The ability to store thermal energy is critical to ensuring a continuous supply of heat during periods of low solar radiation, allowing for more precise control of the internal environment. The 18 mentions of “solar

radiation” reinforce the importance of this factor in the design of greenhouse systems, while the inclusion of terms such as “air conditioning—solar energy systems” and “crops”, both with 16 mentions, suggests that research is not only focused on infrastructure, but also on the impact these technologies have on the quality and quantity of agricultural production. Together, these terms provide a comprehensive view of how current research is addressing the intersection between solar energy and controlled agriculture in order to increase productivity in a sustainable manner.

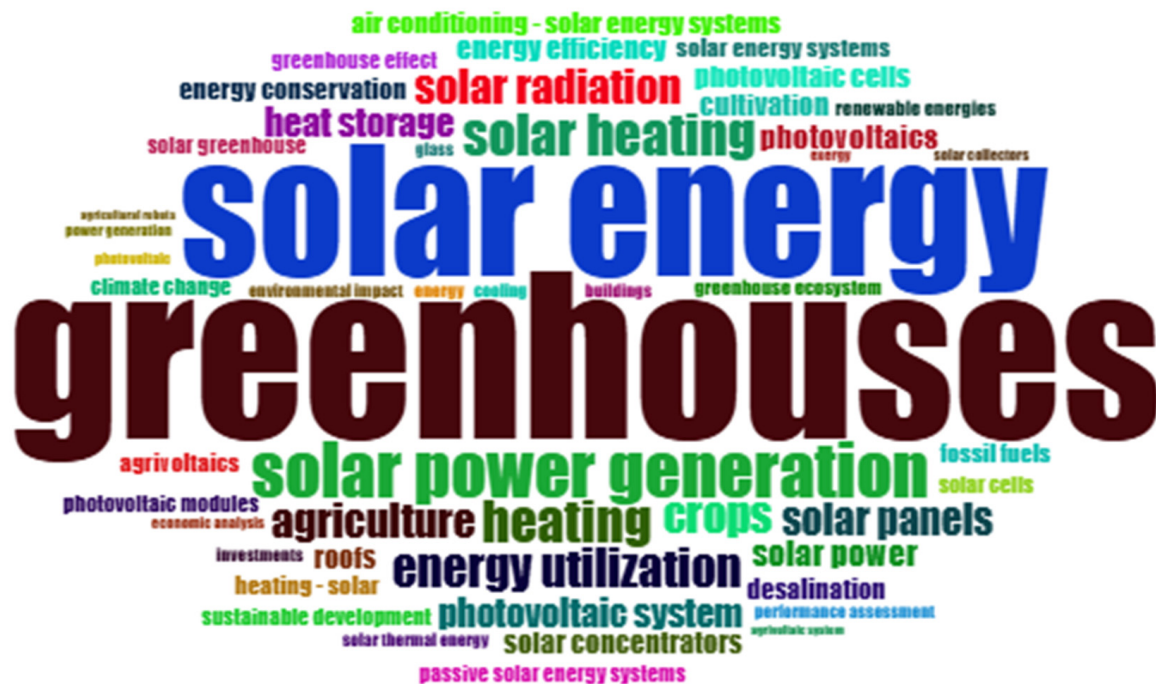


Figure 5. A cloud of keywords found in the literature analyzed.

Following on from the analysis in the previous figure, Figure 6 shows the keyword co-occurrence map, which provides a visual representation of the relationships between the terms most frequently used in the literature [92]. This map allows us to visualize how key concepts, represented as nodes of different sizes, are grouped around specific thematic areas [93]. The proximity between keywords has a direct impact on the formation of textual clusters, which facilitates the identification of recurrent themes and predominant approaches in the field of solar energy applications in greenhouses and protected agriculture.

In order to perform a more detailed cluster analysis using a co-occurrence graph, it is crucial to pay attention to the colors used to group the nodes, as they represent different areas of research [94]. Each color highlights a particular thematic line within the study, allowing the accumulated knowledge to be segmented into distinct sub-disciplines. This approach facilitates the understanding of research and development dynamics, revealing the main trends, gaps, and opportunities at the intersection of solar energy and protected agriculture.

Red and orange cluster—greenhouses and energy efficiency: This cluster encompasses terms that highlight the central role of greenhouses in protected agriculture, with an emphasis on solar power generation and energy efficiency. The following terms stand out: “greenhouses”, “solar power generation”, “energy efficiency”, “heating”, “fossil fuels”, “roofs”, “agriculture”, “cost effectiveness”, and “sustainable development”. Key words such as “fossil fuels” suggest a discussion of the transition to cleaner energy sources within greenhouse systems. The terms “cost effectiveness” and “sustainable development” reinforce the importance of the fact that the technologies implemented are not only energetically viable, but also economically and environmentally viable. Finally, in this cluster, the papers focus on the evaluation and discussion of how solar energy systems, integrated into green-

in the OPV tunnels were higher than in the control tunnels, evidencing the benefit of this technology in improving the microclimate and agricultural production [98].

Blue cluster—heat storage and transfer systems: This group explores technologies related to heat storage, energy transfer, and the availability of water resources within greenhouse systems. In this cluster, there are terms such as “heat storage”, “heat transfer”, “solar stills”, “energy saving”, “dehumidification”, and “thermal energy storage”. In this sense, terms such as “solar stills” and “energy saving” suggest that the studies seek or promote the use of low-consumption technologies in order to maintain the stability of the microclimate throughout the year. Additionally, terms such as “dehumidification”, a factor that can affect both growth and crop health [99], allow us to infer that works dedicated to dehumidification are essential to efforts to establish a strategy with which to control excessive humidity [69]. On the other hand, the term “desalination” indicates that desalination studies may be focused on the search for solar systems that can convert saline water into water that is suitable for irrigation, optimizing the use of water resources in arid or coastal areas [100]. All these systems, which take advantage of solar energy, are essential in order to improve both energy efficiency and water efficiency in protected agriculture, even in regions where climatic conditions are adverse.

Purple cluster—the use of photovoltaic energy and heat pumps: This cluster mainly focuses on the use of photovoltaic energy and heat pump systems when applied to greenhouses, suggesting that there is a focus on the integration of renewable energy sources to optimize energy consumption in these food production systems [101]. Key terms, such as “photovoltaic cells”, “pumps”, and “heat pump systems”, indicate that much of the research is focused on the use of photovoltaic cells to generate clean electricity by harnessing solar energy to reduce dependence on conventional energy sources [102]. These systems are not only applicable in terms of powering greenhouses, but also provide a constant and efficient energy supply for other critical functions, such as temperature control through heat pumping systems, allowing for more precise control of the microclimate [75]. In addition, terms such as mathematical models indicate that studies are using mathematical models to predict and improve the efficiency of these renewable energy systems, ensuring that the greenhouse performance is optimal in terms of production and sustainability [103]. Finally, the connection with terms such as sustainable development underlines that these technologies are at the heart of the move towards more sustainable agricultural practices that are less dependent on fossil fuels.

Green cluster—climate and energy supply: This cluster focuses on the integration of solar energy for climate and energy supply in greenhouse systems. Key terms such as “solar power”, “solar heating”, and “solar thermal energy” suggest a focus on the use of renewable energy to maintain optimal conditions inside greenhouses, particularly through solar heating [104]. In addition, concepts such as “performance assessment” and “heat storage” indicate that thermal storage technologies are being studied that allow heat to be stored during the day for use at night or during periods of lower solar radiation [55]. The term “cooling” shows that solar cooling is key in hot climates, helping to maintain the right temperature for crop growth [105]. Finally, the presence of “economic analysis” and “investments in solar thermal energy” highlights the importance of assessing the economic viability of these systems and the investments required for their implementation [106]. Overall, this cluster reflects the trend towards sustainability and energy efficiency in protected agriculture through the adoption of advanced solar technologies that reduce dependence on fossil fuels and optimize the use of resources.

Seawater-blue cluster—solar concentrators and photovoltaic systems: This cluster focuses on the development of technologies related to photovoltaic (PV) systems and solar concentrators, which are crucial in effort to improve energy efficiency in greenhouses [107]. Terms such as “PV system” and “concentrators” indicate a focus on solutions that allow the capture and concentration of sunlight in a small area, maximizing the energy production needed for microclimate control inside greenhouses. These technologies are especially important in regions with high levels of solar irradiation, since they optimize both energy

generation and the use of water and thermal resources, favoring greater sustainability in protected agriculture [108]. When integrating solar concentrators with photovoltaic systems, greenhouses not only generate clean energy, but also ensure greater energy independence, allowing the more efficient use of sunlight in order to maintain ideal growing conditions [109].

3.10. Thematic Map

The thematic map shown in Figure 7 is used in bibliometric analyses to assess the relationships and development of themes within a specific research area [110]. It is divided into four quadrants, each one indicating the level of relevance (centrality) and the degree of development (density) of the research topics [111]. The X axis represents the centrality of each topic, indicating its importance and level of connection to other topics within the field of study. A higher value on the X axis suggests that the topic is more central and plays a crucial role in the research area. The Y axis measures the degree of development of the topic, reflecting its maturity and consolidation. A high value on this axis implies that the topic is well developed, with a solid bibliographic base, while a low value suggests that the topic is emerging or in decline [112].

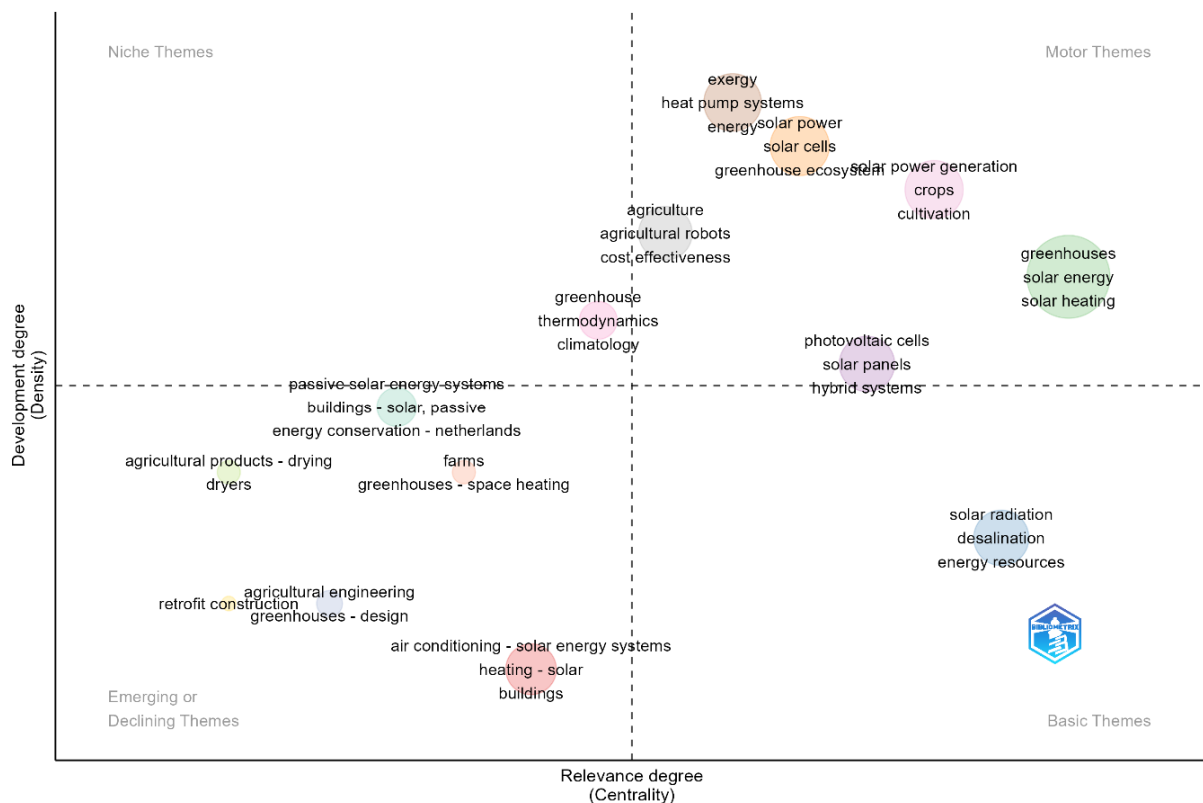


Figure 7. A conceptual thematic map of the area of knowledge.

The upper-right quadrant is the area of driving themes, i.e., those with high centrality and high density [113]. This indicates that they are not only well developed, but are also relevant topics that drive the evolution of the research field. In the graph, terms such as “greenhouses”, “solar energy”, “solar heating”, and “solar power generation” are highlighted. These topics are essential in the context of integrating solar energy with agricultural structures and represent areas of great academic and practical interest. The size of the “greenhouse” bubble is particularly large, suggesting that there is a large amount of scientific output around the optimization of solar-powered greenhouses to improve agricultural yield and energy efficiency. The presence of terms such as “crops” and “cultivation” indicates that protected agriculture and the use of renewable energy

technologies in food production are key areas of interest. The combination of “solar energy” with “solar heating” highlights the importance of greenhouse-heating technologies, especially in cold climates or during seasons with low levels of solar irradiation. Together, these topics represent the core of development in renewable energy research for protected agriculture, displaying strong links to sustainable growth and efficient food production.

The upper-left quadrant groups niche themes, characterized by high density and low centrality [111]. These are well developed but specialized topics, with a specific focus that does not connect strongly with other topics in the research network. In this quadrant, terms such as “exergy”, “heat pump systems”, and “greenhouse ecosystems” are found. The high density of these topics indicates that they are areas with a solid base of knowledge and development, but that they do not yet display significant integration with the global research core. The term “exergy” refers to thermodynamic efficiency and effective energy use, a technical topic that is explored in depth in advanced energy system contexts. Although relevant, its specific applicability limits its centrality. On the other hand, the phrase “heat pump systems” refers to a topic with high levels of development in terms of heat recovery and optimization technologies, especially in climates where temperature management is critical for agricultural production. Finally, the term “greenhouse ecosystems” indicates a focus on the sustainability and balance of microclimates within greenhouses. This is of interest for the development of environmentally responsible solutions but remains a niche topic within the broader context of renewable energy and agriculture.

The lower-right quadrant includes the basic themes. These have high centrality but low density, which means that, although they are fundamental to the field, they are not yet fully developed [114]. In this quadrant, we find terms such as “photovoltaic cells”, “solar panels”, “hybrid systems”, and “solar radiation”. Their placement suggests that they are fundamental technologies and concepts for the implementation of solar solutions in agriculture, but they require further research and practical applications to become established as driving themes. The position of “photovoltaic cells” and “solar panels” as basic topics highlights the importance of photovoltaic technologies in power generation for agricultural applications, but their low density indicates that they have not yet been explored in sufficient depth to optimize their use in protected environments such as greenhouses. The phrase “hybrid systems” also refers to an important concept involving the combination of different energy sources (solar, wind, geothermal) to improve the energy efficiency of agricultural operations. However, its low density indicates that work is needed in order to fully integrate it into agricultural solutions. These basic themes represent a solid foundation on which future research can be built, connecting different technological approaches.

The lower-left quadrant includes topics with low centrality and low density. These may be emerging topics with growth potential or declining topics that are losing popularity among the scientific community [113]. In this graph, terms such as “passive solar energy systems” and “agricultural engineering” are found. These topics show initial or limited development, which could be due to a lack of attention or declining popularity in the field at present. “Passive solar energy systems” implies the use of solar energy without additional mechanical equipment, which may be of interest in the development of low-cost energy solutions but is currently not very relevant in the agricultural context or lacks development.

3.11. Multiple Correspondence Analysis

The graph presented in Figure 8 corresponds to a multiple correspondence analysis, which is a technique used in bibliometric studies and data analysis to evaluate the relationships between themes or keywords in a set of information. This type of analysis allows us to visualize associations and patterns between categorical variables, facilitating the identification of clusters and underlying relationships in the data set [115]. The structure of the graph is defined in terms of two main axes: the X axis (Dim 1), which explains 36.58% of the total variability, and the Y axis (Dim 2), which explains 20.39% of the variability [116]. Together, both dimensions capture 56.97% of the variability in the data, which means that

more than half of the relationships and thematic patterns present in the field of study can be interpreted from this graph. The remaining percentage (43.03%) is distributed in other dimensions not represented here, suggesting that there are additional relationships that are not visible in this graph. The terms are grouped into different clusters, each with a distinctive color, reflecting areas of research that share similarities or common contexts.

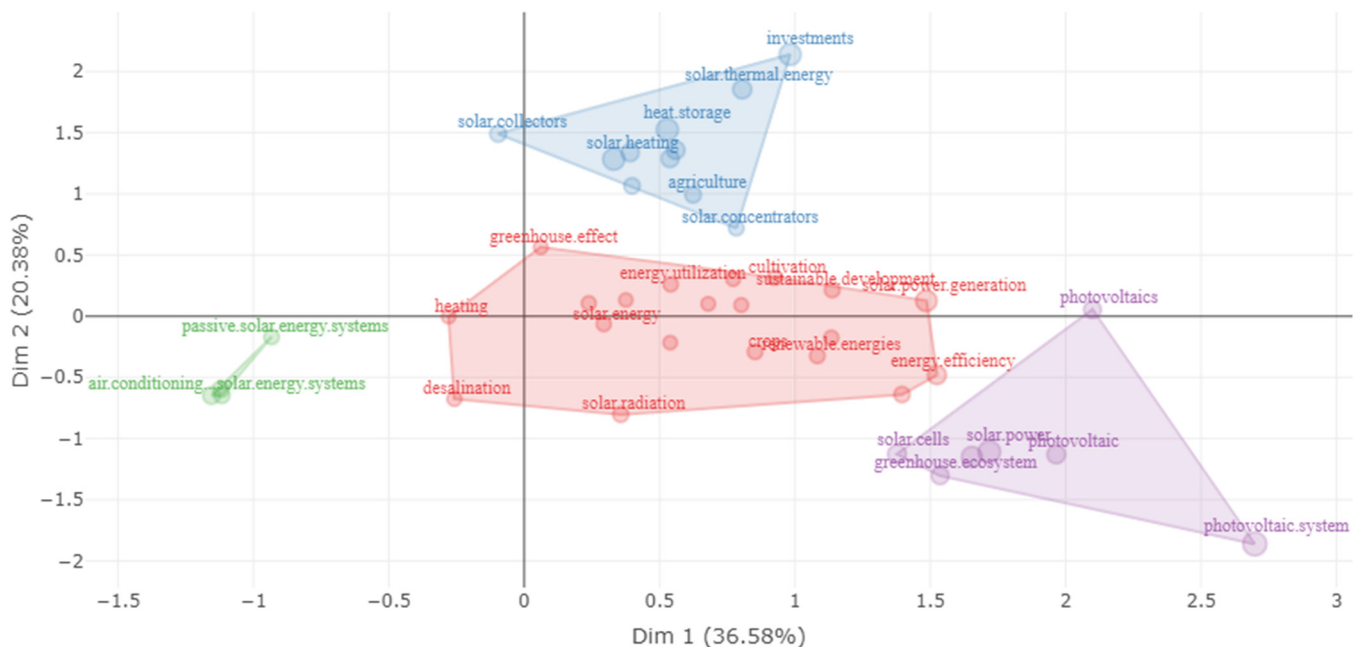


Figure 8. Conceptual structure map created using multiple correspondence analysis.

The green cluster, located on the left side of the graph, groups terms such as “passive solar energy systems” and “air conditioning—solar energy systems”, reflecting issues related to energy efficiency and the use of passive solar systems. Passive systems are characterized by their ability to harness solar energy without the need for additional mechanical equipment, such as natural ventilation, or a bioclimatic architecture. The proximity of these terms suggests that they share a common focus on energy conservation and sustainability in applications such as building air conditioning and environmental conditioning. This cluster is distinguished by its specialization in methodologies that maximize the use of solar energy at a low cost, without requiring complex conversion technologies, which makes it a relevant area for the development of sustainable solutions, especially in regions seeking to reduce dependence on active energy systems.

The red cluster, located in the central area of the graph, is composed of terms such as “greenhouse effect”, “cultivation”, “agricultural development”, and “solar power generation”. This cluster focuses on the relationship between agriculture and solar energy applications in order to optimize the microclimate and improve production efficiency in greenhouses. The themes of this cluster indicate a focus on how solar energy can be used to modify the growing environment in order to increase agricultural productivity while minimizing the use of external inputs. The density of this cluster suggests a strong interest in combining agricultural technologies and renewable energy to maximize sustainable food production, positioning it as a key area in developing integrated strategies for climate control and reducing the environmental impact of intensive agriculture.

The blue cluster, located at the top of the graph, groups terms such as “solar cells”, “solar panels”, and “solar collectors”, representing the core of research into photovoltaic technologies. This cluster focuses on the conversion of solar energy into electricity, exploring both improvements in solar cell efficiency and the implementation of solar collectors for various applications. The presence of these terms in a separate cluster suggests that photovoltaic technologies are specialized and relatively disconnected from the agricultural topics

present in other clusters. Research in this cluster is more oriented to the optimization of energy efficiency and the integration of these systems into urban and rural infrastructures. Its location in the graph reflects the need to deepen the interactions of these technologies with other energy systems and agricultural applications to achieve more effective integration.

The purple cluster, located on the right of the graph, groups terms such as “hydrolysis”, “efficiency”, and “solar energy conversion”. This cluster focuses on energy conversion technologies and energy efficiency, with a focus on chemical and biochemical techniques for energy harvesting and their possible use in the context of producing hydrogen or other biofuels from solar energy. The presence of hydrolysis suggests an interest in processes for converting solar energy into chemical fuels, representing an area of advanced research with implications for both energy generation and sustainability. This cluster is relatively separate from the others, indicating that chemical conversion issues are not directly connected to the agricultural or architectural contexts represented in other clusters. However, its high density suggests that it is a mature and well-developed area within the renewable energy field.

4. Gaps in Existing Technologies and Future Research Directions

The current landscape of photovoltaic and climate control technologies in protected agriculture, as illustrated in the multiple correspondence analysis (Figure 8), reveals certain gaps in relation to optimizing energy usage while maintaining crop growth conditions. Technologies that integrate solar energy, such as photovoltaic cells and solar thermal systems, demonstrate potential for reducing reliance on traditional power sources, yet face limitations in efficiency, particularly under variable climatic conditions. The scattered distribution of terms like “solar energy system”, “greenhouse effect”, and “energy efficiency” within the clusters suggests that existing systems struggle to maintain consistent performance across different environmental contexts. This variability limits the scalability of such solutions, especially in diverse agricultural setups, indicating the need for further refinement in adaptable energy technologies.

Moreover, there is a noticeable gap in the comprehensive deployment of data-driven climate control systems that fully utilize artificial intelligence (AI) and the Internet of Things (IoT). While terms like “data-driven systems” and “remote monitoring” appear as emerging themes, the integration of these digital tools remains limited. Existing systems are often constrained by issues such as high initial setup costs, limited sensor accuracy, and insufficient interoperability between different systems, hindering the widespread adoption of automated, responsive climate control solutions. This gap signifies an opportunity for further advancements in affordable, high-precision sensors and robust AI algorithms tailored for real-time agricultural applications.

Future research should focus on hybrid solutions that combine photovoltaic technologies with advanced climate control mechanisms to optimize energy and resource usage in greenhouses. The analysis reveals a growing interest in themes related to “solar cells”, “energy storage”, and “sustainable development”, suggesting that a key research direction involves enhancing energy efficiency through integrated systems. Hybrid models could leverage solar energy, not only for electricity generation but also for active climate regulation. This could be applied in heating, cooling, and humidity control to create a more stable microclimate for crop growth. This approach would address existing gaps by ensuring a consistent performance and maximizing energy independence in greenhouses, especially in regions with fluctuating sunlight levels.

Another promising research area lies in the advancement of bioclimatic design and passive energy technologies for greenhouses, particularly for applications in hot or arid regions where traditional cooling solutions are energy-intensive. The cluster containing terms like “passive energy” and “air conditioning—solar energy systems” highlights the necessity of low-energy, sustainable designs that can reduce dependence on active cooling and heating. Developing materials and architectural features that naturally regulate temperature and humidity could pave the way for more sustainable greenhouse models, ensuring optimal growth conditions while minimizing energy input.

5. Conclusions and Recommendations

Research in the application of solar energy to protected agriculture is led by the Netherlands and India, standing out for both scientific production and international collaboration. Institutions such as Wageningen University & Research and journals such as *Acta Horticulturae* and *Solar Energy* play a key role in knowledge dissemination. The co-authorship and citation network reflects the interdisciplinarity of the field, combining technological innovation and sustainable practices to meet today's agricultural challenges.

The integration of advanced solar technologies into greenhouse tomato production has proven to be critical to efforts to optimize energy efficiency, reduce dependence on fossil fuels, and improve crop sustainability. Initiatives such as hybrid systems with thermal storage, 3D ray tracing models, and organic solar cells (OSCs) have led to increased productivity and reduced energy costs, especially in adverse climates. These advances underscore the viability of energy-autonomous greenhouses, while posing economic and operational challenges, such as efficient moisture and CO₂ management.

The analysis of keywords and co-occurrence reveals the main research areas related to solar energy's application in greenhouses and protected agriculture. The identified clusters highlight key trends in research, such as the integration of photovoltaic technologies, energy storage systems, efficient air conditioning, and advanced energy conversion. The importance of maximizing energy efficiency and sustainability through the implementation of solar technologies, such as solar panels, concentrators, and solar heating systems, especially in regions with high irradiation, is underlined.

The thematic map indicates that the integration of solar energy in protected agriculture is a central and growing area, with many developments in greenhouse technologies and the optimization of energy resources. While some topics, such as solar heating and greenhouse crop management, are well established and drive research, there are other areas, such as passive systems and the use of photovoltaic cells, that still need further development and exploration.

Multiple correspondence plot analysis identifies four key research areas: passive energy systems, photovoltaic technologies, agricultural applications, and advanced energy conversion. These clusters suggest opportunities to integrate solar technologies with agricultural production, optimizing energy efficiency and productivity in greenhouses. They also highlight the importance of developing low-power solutions and exploring the production of biofuels and hydrogen using solar energy. The integration of digital technologies such as remote monitoring and artificial intelligence will be fundamental in efforts to improve climate control in greenhouses and move towards sustainable and resilient agriculture.

It is recommended that future research explore hybrid greenhouse models that combine solar technologies with other renewable sources. In addition, it would be relevant to develop local and regional scale studies that analyze the dynamics of implementation under different climatic and economic conditions. An interdisciplinary approach, integrating knowledge in engineering, environmental sciences, and agricultural economics, will be key to further optimizing these technologies and ensuring their scalability and profitability.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agronomy14122791/s1>, Table S1: Review greenhouse; Doc S1: PRISMA 2020 Checklist; Doc S2: PRIS-MA_Protocol_Greenhouses_Solar.

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