Advances in Applied Sciences
2024, Vol. 9, No. 1, pp. 6-16
https://doi.org/10.11648/j.aas.20240901.12

Review Article

Research Progress in Facility Agriculture and Lighting by Bibliometric Analysis Based on CiteSpace

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Abstract

Given the pressures of internation-al market competition, the dual constraints of domestic resources and the environment, and the uncertainties posed by climate change, bolstering agricultural infra-structure construction is a realistic demand and a crucial approach for implementing emerging grain security strat-egies, particularly in developing countries. Facility agriculture is characterized as a modern agricultural production mode that improves or creates favorable environmental conditions within a specific locality. With the rapid expansion of large-scale facility agriculture, there has been an increased demand for various types of energy, including electricity, gas, cold, and heat. Agricultural lighting equipment used in facility agriculture is a modern agricultural technique that applies engineering technology to regulate light supplementation in the production process. Facility lighting offers several advantages over traditional methods, such as higher photovoltaic conversion efficiency, adjustable spectrum, high photosynthetic efficiency, energy efficiency, environmental friendliness, long lifespan, monochromatic light, cold light source, and compact size. Promoting national food security, carbon neutrality, returning farmland to forests, and implementing low-carbon green agricultural policies all contribute to the favorable use of facility agriculture lighting. This study aims to provide a systematic summary of the relevant research conducted in the past decade using Citespace software. The advantage of facility agriculture for carbon sequestration capacity can effectively reduce net carbon emissions from facility agricultural production activities. In addition, the combination of agriculture and the Internet of Things can effectively improve agricultural production efficiency and economic returns. Combining artificial intelligence and other technologies with facility agriculture engineering, based on multi-source data fusion, intelligent early warning for facility agriculture energy internet can be used to prevent agricultural meteorological disasters. More importantly, it helps maintain global food security, eliminate hunger, and reduce economic inequality. The findings of this study will contribute to a deeper understanding of agricultural lighting equipment, serving as a new theoretical foundation for achieving agricultural emission reduction targets and promoting agricultural technical cooperation.

Keywords

Facility Agriculture, Citespace, Lighting, Carbon Neutrality, Sustainability

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Received: 3 February 2024; **Accepted:** 21 February 2024; **Published:** 7 March 2024

1. Introduction

Agriculture, as the second-largest source of carbon emissions after industry, currently accounts for approximately one-fifth of global anthropogenic carbon emissions. It is crucial to promote agricultural economic development while implementing a green and low-carbon agricultural model. This represents the primary focus of future agricultural development [1]. Strengthening the policy system for agricultural infrastructure investment demonstrates countries' attention and emphasis on agricultural development. Agricultural infrastructure construction also serves as a vital means to achieve grain storage capacity and technological advancements. Given the pressures of international market competition, the dual constraints of domestic resources and the environment, and the uncertainties posed by climate change, bolstering agricultural infrastructure construction is a realistic demand and a crucial approach for implementing emerging grain security strategies, particularly in developing countries [2, 3].

Facility agricultures are characterized as a modern agricultural production mode that enhances or creates favorable environmental conditions within a specific locality. They provide controlled environmental settings and efficiently produce crops and animals [4]. This production method adheres to standardized technical specifications, intensive and large-scale management practices, and combines modern biotechnology, agricultural engineering, environmental control, management, and information technology [5]. Reliance on modern facility agriculture ensures a high level of technological expertise, increased product value, improved land productivity, and enhanced labor productivity. Noteworthy examples of its application are found in the high-tech greenhouses in the Netherlands, drip irrigation projects in Israel, plant factories in Japan, and greenhouse production in China [6]. Facility agricultures, as representatives of modern agriculture, are widely utilized in agricultural production bases and agricultural science and technology demonstration centers. They make an irreplaceable contribution to improving people's living standards [7]. Facility agricultures are extensively employed in developed countries in various agricultural sectors such as vegetable, flower, pig farming, poultry breeding, and fishery. They are continually evolving towards greater efficiency, higher output value, and increased profitability. In China, the development of animal husbandry facilities has been rapid, and the technology has become mature. Facility plants units, as the primary form of facility agricultures, have made significant progress in developed countries globally [8].

With the rapid expansion of large-scale facilities agriculture, there has been an increased demand for various types of energy, such as electricity, gas, cold, and heat. This demand arises from the application of technology and the utilization of automated equipment. The low-carbon and clean integrated energy supply in facilities agriculture has gradually become a crucial foundation for the sustainable, eco-friendly development of the agricultural economy [9]. The adoption of adjustable energy supply facilities in agriculture not only expands the use of agricultural energy-consuming equipment but also enhances the modernization level of facilities agriculture. Additionally, it contributes to the reduction of carbon emissions associated with agricultural energy consumption [10].

In recent years, advanced agricultural production technology has been increasingly integrated into various agricultural activities. Among these advancements, facilities agriculture has emerged as a pioneer in the application and development of high-tech equipment [11]. The implementation of high-tech equipment in facilities agriculture has led to a higher level of demand for agricultural energy in terms of both quantity and diversity. Agricultural lighting equipment used in facility agriculture is a modern agricultural technique that applies engineering technology to regulate light supplementation in the production process. This technique aims to achieve efficient production of both animals and plants [12]. Light plays a crucial role in the growth and development of animals and plants. Facility lighting offers several advantages over traditional methods, such as higher photovoltaic conversion efficiency, adjustable spectrum, high photosynthetic efficiency, energy saving, environmental friendliness, long lifespan, monochromatic light, cold light source, and compact size [13, 14]. Developed countries like the United States, Netherlands, and Japan have rapidly embraced intensive facility agriculture due to the integration of modern industry into agriculture and the application of microelectronics technology. The promotion of national food security, carbon neutrality, returning farmland to forest, and implementation of low-carbon green agricultural policies all contribute to the favorable facility agriculture lighting [15, 16].

The significance of infrastructure to social and economic development has been widely acknowledged by scholars. Previous studies have consistently demonstrated that infrastructure plays a crucial role in promoting economic growth. It was confirmed that infrastructure investment accelerates economic growth but also highlights its positive impact on alleviating poverty and reducing income inequality [17, 18]. The development of facility agriculture technology in agricultural countries worldwide is currently progressing rapidly, leading to active research on facility agricultural lighting equipment. This study aims to provide a systematic summary of the relevant research conducted in the past decade (2013-2023) using Citespace software [19]. The findings of this study will contribute to a deeper understanding of agricultural lighting equipment, serving as a new theoretical foundation for achieving agricultural emission reduction targets and promoting agricultural technical cooperation.

2. Materials and Methods

2.1. Data Sources

The data comes from the WOS core database. The search topics were Facility agricultural and lighting, Facility agriculture and lighting, Facility agricultural and Artificial lighting, Facility agriculture and Artificial lighting, Agricultural and lighting, the document type is Article or Review. A total of 5115 literatures from 2013 to 2023 were obtained by CiteSpace. The search time was September 12, 2023, and the visiting institution was Jiangsu University of Science and Technology.

2.2. Research Methods

This text is based on 5115 de-duplicated articles, utilizing the CiteSpace software version V6.2.R4 for visualized network analysis. The analysis includes visual representations of author collaboration networks, institutional collaboration networks, national collaboration networks, co-occurrence and burst of keywords, and a citation map. The data spans from January 2013 to September 2023, segmented annually, with each time slice graphically depicting the top 50 (Top N=50) nodes.

2.3. Analysis of the Annual Publication Volume

Since 2013, the annual publication volume has been steadily increasing (Figure 1) (Note: The literature retrieved for this article is until September 12, 2023; therefore, the literature for 2023 has no reference value for annual publication trends). This indicates a continuous rise in interest in this research field, accompanied by a gradual advancement in the research system. The research can be divided into three stages of slow growth, moderate growth, and rapid growth. The period from 2013 to 2016 represents a slow growth stage, with a relatively low publication quantity and small interannual differences. From 2016 to 2019, there is a moderate growth stage characterized by a significant increase in annual publication volume and growth rate compared to the previous stage. The period from 2019 to 2022 signifies a rapid growth stage, with a notable surge in annual publication quantity and growth rate, indicating vigorous development in the field. As depicted in Figure 1, the turning points in growth occur in 2016 and 2019, suggesting that publications before 2016 and those between 2016 and 2019, likely with classic works, have driven the overall progress in the field.

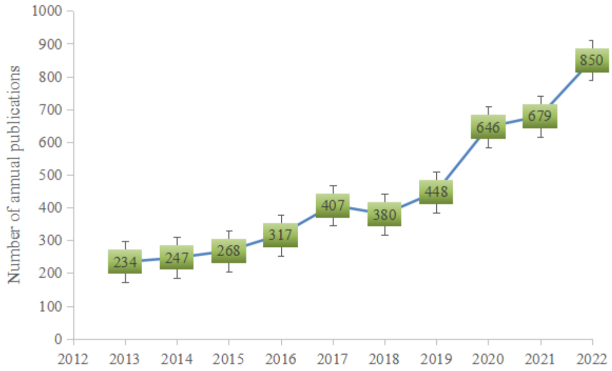

Figure 1. *Annual number of publications (2013-2022).*

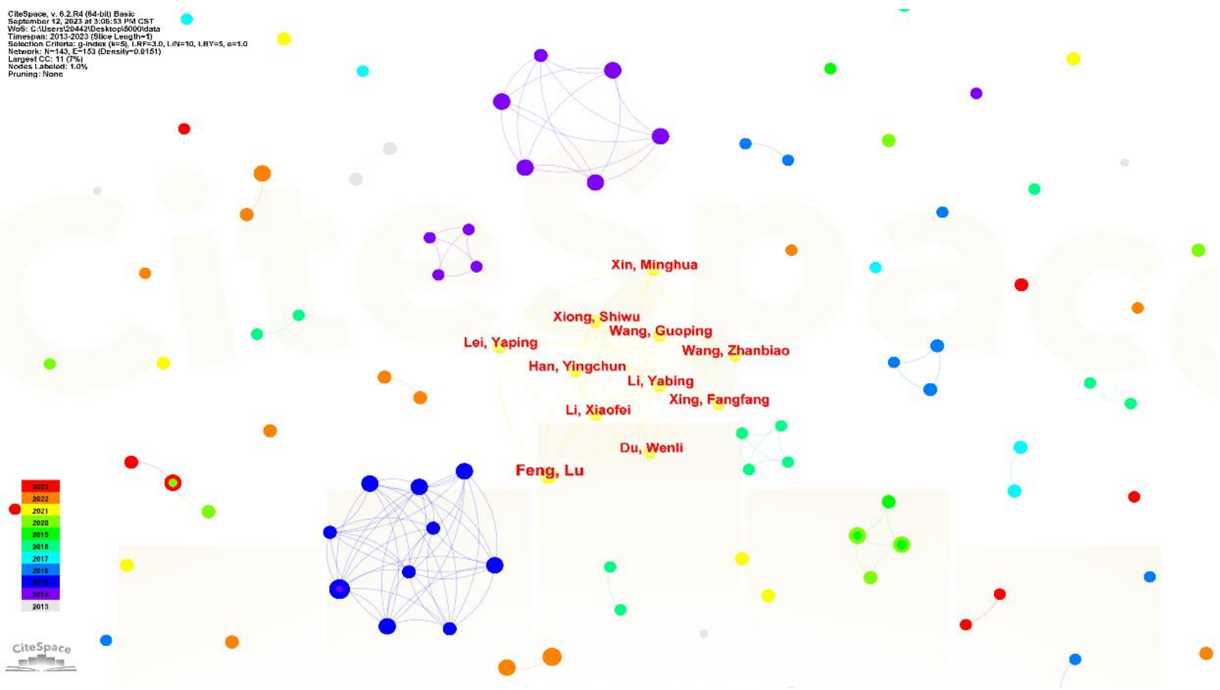

Figure 2. *Author cooperation network.*

3. Results

3.1. Author Cooperation Network

Utilizing CiteSpace for visual analysis, Figure 2 illustrates the collaborative network among authors in this field. Nodes represent authors, and the edges between nodes depict collaborations. The size of nodes correlates with the authors' publication volume. Different colors of annual rings on nodes represent articles published in different years, with the thickness of the rings proportional to the number of articles published in that year. The years corresponding to the different color rings are located in the lower-left section of the graph, with red indicating 2023 and decreasing in subsequent years. N (nodes) = 143, indicating a network composed of 143 authors. D (density) = 0.0151, reflecting a relatively low collaborative network density, suggesting a lower level of collaboration among authors [20].

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Table 1 displays the top 20 authors by publication volume, with Balkew Meshesha (Univ Addis Ababa, Aklilu Lemma Inst Pathobiol, Addis Ababa, Ethiopia) having the highest number of publications. His primary research focuses on sand fly fauna and biological characteristics related to visceral leishmaniasis. The second and third in publication volume are Wang Jing (School of Information Science and Engineering, Shandong Agricultural University, China) and Blondeel Haben (Univ Ghent, Dept Environm, Forest & Nat Lab, Melle Gontrode, Belgium). They have limited collaborations with other scholars, forming two distinct research communities.

Table 1. *Top 20 authors with publications.*

Author Name	Article number
Balkew, Meshesha	6
Wang, Jing	5
Blondeel, Haben	5
Zhang, Yi	4
Yared, Solomon	4
Yang, Yang	4
Warburg, Alon	4
Wang, Peng	4
Wang, Lei	4
Tekie, Habte	4
Oard, James H	4
Linscombe, Steven D	4
Harrell, Dustin L	4
Hailu, Asrat	4
Groth, Donald E	4
Gebre-michael, Teshome	4
Feng, Lu	4
Escola, Alexandre	4
De lombaerde, Emiel	4
Chen, Xi	4

3.2. Institutional Cooperation Network

The institution collaboration network in this field, visualized using CiteSpace, is depicted in Figure 3. It consists of 151 institutions forming connected nodes, with a network density (D) of 0.0582. This network density is higher than that of the author collaboration network, indicating a relatively high level of collaboration among institutions. The maximum intermediary centrality among institutions is 0.32, held by the Chinese Academy of Sciences, suggesting a substantial degree of collaboration between institutions. Intermediary centrality measures how often a node lies on the shortest paths between other pairs of nodes, ranging from 0 to 1. A node with high intermediary centrality either has strong connections with other nodes or connects different clusters.

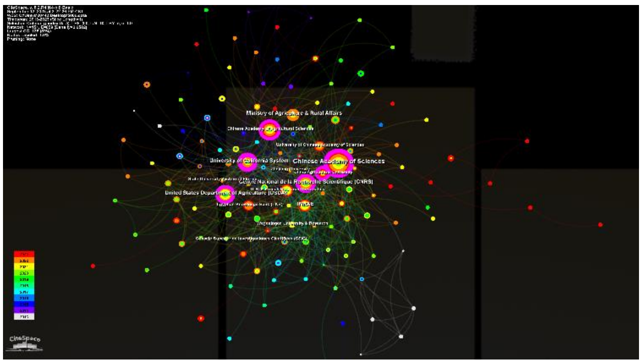


Figure 3. *Institutional cooperation network.*

Table 2 lists the top 20 institutions by publication volume. As indicated, these institutions are predominantly higher education establishments. The Chinese Academy of Sciences holds the highest publication volume among all institutions, exhibiting the highest intermediary centrality and the strongest connections with other institutions. The second and third positions in publication volume are held by the United States Department of Agriculture and the University of California System. Seven Chinese institutions are among the top 20, namely the Chinese Academy of Sciences, University of Chinese Academy of Sciences, Chinese Academy of Agricultural Sciences, China Agricultural University, Zhejiang University, Northwest A&F University, and Nanjing Agricultural University.

Table 2. *Top 20 Institutes for publications.*

Affiliations	Publications number	Intermediary centrality
Chinese Academy of Sciences	256	0.32
United States Department of Agriculture	121	0.16
University of California System	112	0.28
Centre National de la Recherche Scientifique	112	0.15
Ministry of Agriculture & Rural Affairs	102	0.08
INRAE	95	0.09
UDICE-French Research Universities	87	0.08
University of Chinese Academy of Sciences	86	0.04
Chinese Academy of Agricultural Sciences	84	0.12
Egyptian Knowledge Bank	79	0.03
China Agricultural University	71	0.14
Wageningen University & Research	57	0.05
Consejo Superior de Investigaciones Cientificas	55	0.03
Zhejiang University	51	0.02
State University System of Florida	50	0.06
Northwest A&F University - China	42	0.04
Nanjing Agricultural University	38	0.08
Indian Council of Agricultural Research	38	0.05
Helmholtz Association	37	0.04
Universidade de Sao Paulo	34	0.00

3.3. National Cooperation Network

The national cooperation network in this field drawn by CiteSpace is shown in Figure 4. There are 108 associated nodes; D = 0.184, compared with 0.0151 of the author cooperation network and 0.0582 of the institutional cooperation network, the density of the national cooperation network is significantly improved, indicating that international cooperation in this field is relatively close. This result can also be reflected by the maximum value of intermediary centrality 0.21 (France). As shown in Figure 4, the periphery of nodes with betweenness centrality greater than 0.1 is marked in purple, such as France, the United States and Germany.

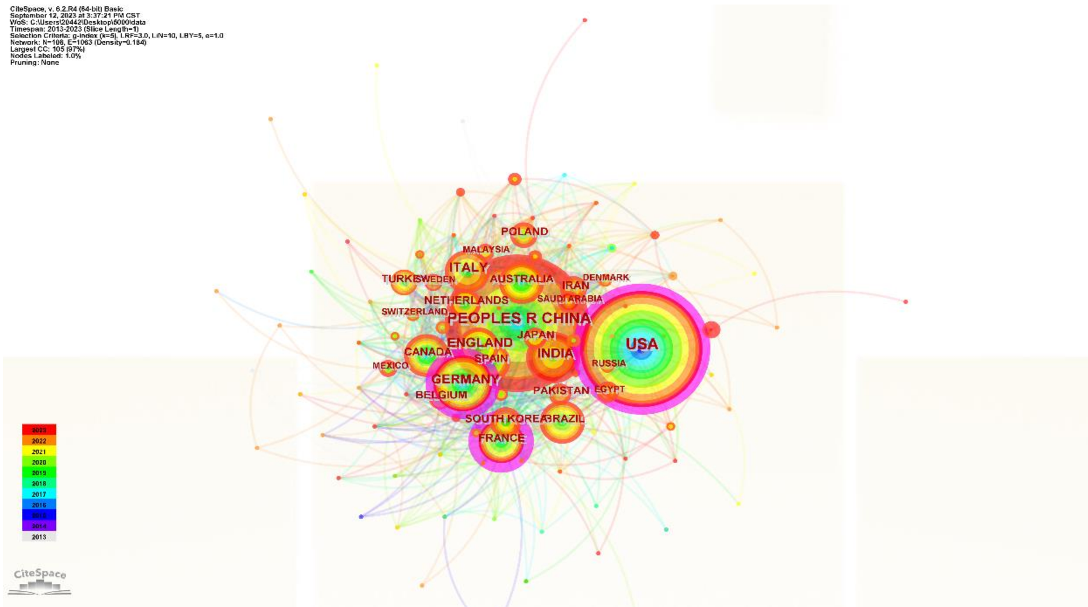


Figure 4. *National cooperation network.*

The top 20 countries (Table 3) are China, the United States, India, Germany, Italy, England, Brazil, Spain, France, Canada, Australia, the Netherlands, South Korea, Japan, Poland, Iran, Turkey, Pakistan, Belgium and Egypt. Among them, China has the largest number of publications, which is equivalent to the sum of the number of publications of India, Germany, Italy and England ranked 3-6. It has made outstanding contributions in this research field. Although China has a large number of publications, the research in this field started late. In 2013, the annual number of publications was 42, while the number of publications in the United States was 63. The countries with an intermediary centrality greater than or equal to 0.1 are the United States (0.14), Germany (0.11) and France (0.21), all of which are European and American countries, indicating that these countries have extensive international cooperation in this field, while China 's intermediary centrality is only 0.02, which is on the periphery of the international cooperation network and needs to strengthen relevant cooperation with other countries.

Table 3. *Top 20 countries for publications.*

Countries	Publications number	Intermediary centrality
China	1346	0.02
USA	1014	0.14
India	366	0.08
Germany	318	0.11
Italy	290	0.09
England	249	0.09
Brazil	234	0.02
Spain	213	0.06
France	212	0.21
Canada	205	0.05
Australia	204	0.06
Netherlands	141	0.05
South Korea	134	0.02
Japan	122	0.02
Poland	122	0.01
Iran	121	0.03
Turkey	106	0.01
Pakistan	92	0.02
Belgium	91	0.06
Egypt	87	0.04

3.4. Keyword Clustering Analysis

Keywords provide a concise overview of the literature's content and theme. Utilizing CiteSpace for keyword co-occurrence analysis (Figure 5) facilitates an understanding of the research content and its current status within the field. The graph consists of 149 associated keywords forming nodes. The nodes feature annual rings in different colors, representing the occurrence of keywords in articles across various years. The corresponding years for each color-coded annual ring can be found in the lower left corner of the map. Table 4 displays the top 20 keywords, including growth, light, management, climate change, yield, water, quality, impact, nitrogen, land use, temperature, behavior, diversity, biodiversity, dynamics, response, model, system, soil, and plant.

Table 4. *Top 20 keywords with highest frequency.*

Keywords	Frequency	Intermediary centrality
Growth	360	0.08
Light	252	0.04
Management	224	0.04
Climate change	220	0.09
Yield	178	0.04
Water	175	0.08
Quality	157	0.05
Impact	156	0.06
Nitrogen	156	0.05
Land use	153	0.03
Temperature	152	0.06
Performance	148	0.04
Diversity	136	0.03
Biodiversity	127	0.04
Dynamics	126	0.04
Responses	124	0.06
Model	118	0.03
System	115	0.06
Soil	114	0.08
Plants	108	0.01

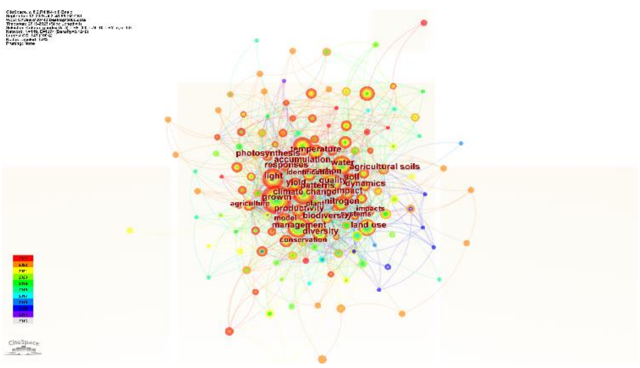


Figure 5. *Keywords co-occurrence analysis.*

Keyword clustering labels were generated using CiteSpace's log-likelihood ratio (LLR) algorithm (Figure 6). The credibility of clustering is evaluated through two indicators: module value (Q) and average contour value (S). A Q value above 0.3 and an S value above 0.5 are generally considered reasonable, while an S value above 0.7 is regarded as highly efficient and credible. In this study, the Q value for keyword clustering is 0.285, indicating potential overlap after clustering. However, the S value is 0.7058, indicating very high clustering credibility. The number of clustering labels corresponds to the number of keywords contained within. According to the clustering results, #0 represents biodiversity, #1 represents photosynthesis, #2 represents photocatalysis, #3 represents model, and #4 represents deep learning, all of which are important research aspects in this field.

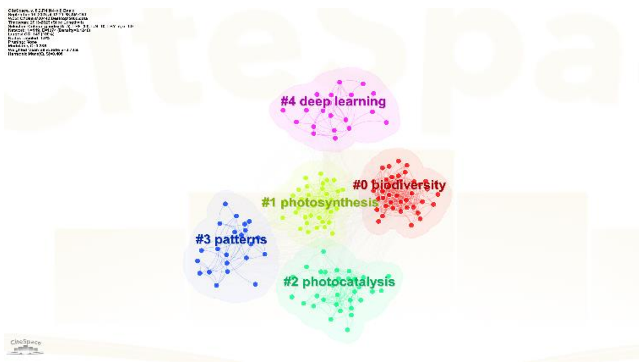
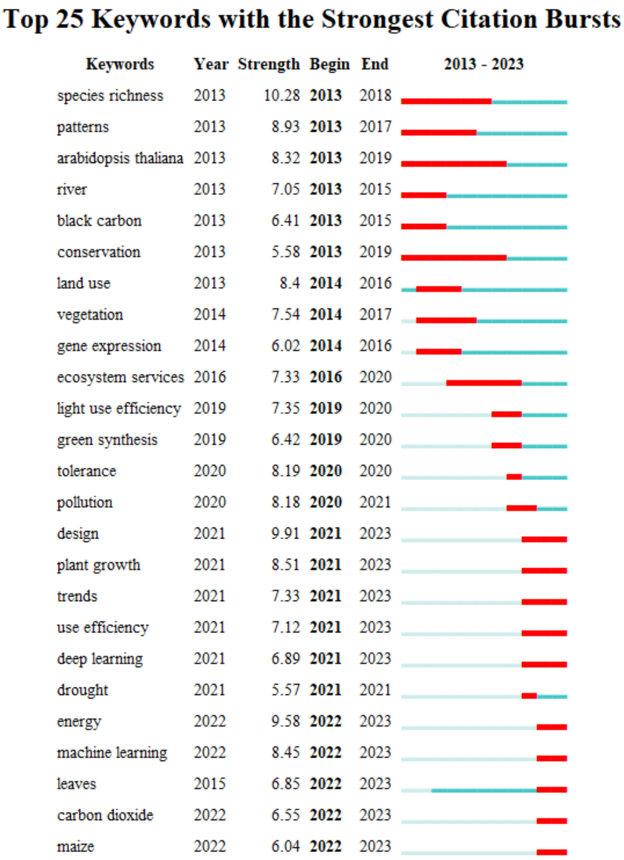


Figure 6. *Keywords clustering analysis.*



Top 25 Keywords with the Strongest Citation Bursts

Keywords	Year	Strength	Begin	End	2013 - 2023
species richness	2013	10.28	2013	2018	
patterns	2013	8.93	2013	2017	
arabidopsis thaliana	2013	8.32	2013	2019	
river	2013	7.05	2013	2015	
black carbon	2013	6.41	2013	2015	
conservation	2013	5.58	2013	2019	
land use	2013	8.4	2014	2016	
vegetation	2014	7.54	2014	2017	
gene expression	2014	6.02	2014	2016	
ecosystem services	2016	7.33	2016	2020	
light use efficiency	2019	7.35	2019	2020	
green synthesis	2019	6.42	2019	2020	
tolerance	2020	8.19	2020	2020	
pollution	2020	8.18	2020	2021	
design	2021	9.91	2021	2023	
plant growth	2021	8.51	2021	2023	
trends	2021	7.33	2021	2023	
use efficiency	2021	7.12	2021	2023	
deep learning	2021	6.89	2021	2023	
drought	2021	5.57	2021	2021	
energy	2022	9.58	2022	2023	
machine learning	2022	8.45	2022	2023	
leaves	2015	6.85	2022	2023	
carbon dioxide	2022	6.55	2022	2023	
maize	2022	6.04	2022	2023	

Figure 7. *Keywords with the strong citation bursts.*

Running the 'Burstness' function with the Minimum Duration set to 1 and other parameters remaining unchanged, 114 burst items were identified, signifying the emergence of 114 keywords as research hotspots in this field. Figure 7 displays the top 25 burst intensity keywords, including species richness, pattern, Arabidopsis, river, black carbon, protection, land use, vegetation, gene expression, ecosystem services, light use efficiency, green synthesis, tolerance, pollution, design, plant growth, trend, use efficiency, deep learning, drought, energy, machine learning, leaves, carbon dioxide, and corn. The occurrence time of keyword nodes, represented by the Year in the graph, is illustrated by a red line segment indicating their emergence. Species richness, design, and energy exhibit substantially higher burst intensity compared to other keywords, with intensities of 10.28, 9.91, and 9.58, respectively. The burst intensity of other burst words is below 9. By examining the emergence of keywords across different years, one can explore the research hotspots at different times.

3.5. Literatures Co-citation Analysis

Co-cited literature refers to the literature cited by the same article, and the number of citations is an important indicator of academic impact. Figure 8 shows the co-citation network in this field, drawn using CiteSpace. The figure includes 215 cited documents, represented as nodes. The size of the nodes correlates with the number of citations they have received. Highly cited documents are considered milestones and have significant breakthroughs. Each node has an outer ring similar to tree rings, with different colors representing different citation years. The thickness of the outer ring indicates the number of citations in that year. The years corresponding to the outer ring colors are shown in the lower left corner of the figure. The connections between nodes indicate that they are cited by the same article. Literature with purple and red outer rings, which represent high betweenness centrality and sudden strength, respectively, along with literature with high citation frequency, are considered important in this field. The top 20 cited literature is presented in Table 5. In this paper, the top three cited literature are analyzed. The most cited literature is "R Core Team, 2019, R LANG ENV STAT COMP, V0, P0." The second article is "Bates D, 2015, J STAT SOFTW, V67, P1, DOI 10.18637/jss.v067.i01." The third article, published by Barron-Gafford in 2019 in 'Nature Sustainability,' is titled "Agrivoltaics provide mutual benefits across the food-energy-water nexus in drylands" (DOI: 10.1038/s41893-019-0364-5). This article discusses the resilience of building renewable energy and food production. From Table 5, it can be observed that two of the top three cited articles were published in 2019, suggesting a trend after this year.

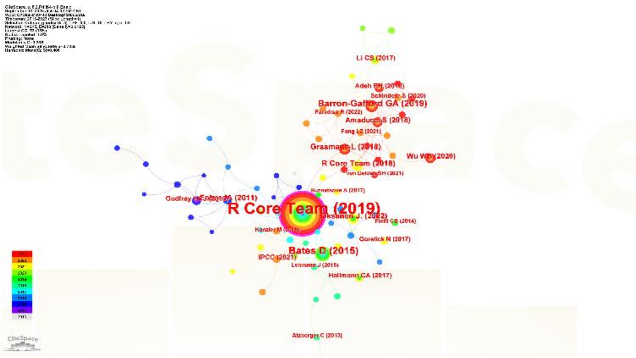


Figure 8. Literatures co-citation analysis.

Table 5. Top 20 articles with highest citation.

Authors	Citation number	Intermediary centrality
R Core Team	223	0.18
Bates D	23	0.02
Barron-Gafford	17	0.02
Graamans L	12	0.06
Oksanen J	12	0.02
R Core Team	12	0.02
Bond TC	11	0.00
Foley JA	11	0.05
Krizhevsky Alex	11	0.00
Bailey-Serres	10	0.00
Amaducci S	9	0.04
Wu WB	9	0.00
Adeh EH	8	0.00
Godfray HCJ	8	0.00
Hallmann CA	8	0.00
Li CS	8	0.01
Li W	8	0.00
Lowry GV	8	0.00
Wang HB	8	0.00
Blasing M	7	0.00

The cited literature serves as the knowledge base for the research field, and the research frontier is identified through knowledge base clustering (Figure 9). The Q value of the cluster is 0.8683, indicating a high level of credibility. The S value is 0.9978, further indicating the reliability of this cluster. The resulting clusters are #0 agricultural photovoltaic, #1 sustainability, and #2 regression analysis. However, the research field undergoes regular knowledge updates, and the timeline diagram of clustering allows for analysis of the development of clustering and the current research frontier. The results show that each cluster has a different duration. Some clusters have remained active for more than ten years, such as #0 agricultural photovoltaic. Currently, the research frontiers receiving more attention are #0 agricultural photovoltaic and #1 sustainability. It is expected that there will be more dynamic research frontiers in the future.

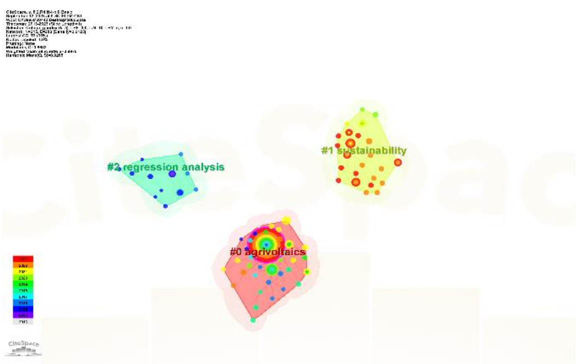


Figure 9. Research frontiers analysis.

4. Research Perspectives

Currently, the development of facility agriculture technology in various agricultural countries around the world is very rapid, and related research is actively being conducted. In recent years, urban agriculture lighting related to facility agriculture has begun to receive attention [21]. Vertical farms and civilian building lighting for vertical agriculture have also only recently begun, with less theoretical exploration and more spontaneous practice. Practices are widely distributed, spanning developed countries such as the United Kingdom, France, Netherlands, Germany, Russia, the United States, and Canada, seeking safer and lower-carbon food [22, 23].

Many countries around the world are also conducting research on the combination of renewable energy and facility agriculture. Current research on agricultural energy usage mainly focuses on the coupling of different types of agricultural energy [23]. Research on energy carbon reduction in facility agriculture is in the early stages. Previous studies have shown that agricultural photovoltaics and sustainable agriculture are research frontiers [24]. Studies have analyzed the beneficial effects of photovoltaic power supply systems in farms, providing reliable experience for clean and economic operation of other facility farms in the region [25]. Using photovoltaic power systems for irrigation pumps in farmland to provide water for irrigation, technical analysis and performance evaluation have verified the feasibility of using photovoltaic energy for facility agriculture energy supply, which has a role in reducing agricultural carbon emissions. Another advantage of facility agriculture is its strong carbon sequestration capacity, which can effectively reduce net carbon emissions from facility agricultural production activities. In addition, the combination of agriculture and the Internet of Things can effectively improve agricultural production efficiency and economic returns [26].

The Arkansas Community Design Center's joint Department of Biological and Agricultural Engineering design of "Fayetteville 2030: Food City Scenario 10" establishes urban agriculture within the city through composting networks, comprehensive waste management facilities, thick bedding agriculture, and urban aquaculture strategies to ensure food security in a doubling population scenario [27]. Combining artificial intelligence and other technologies with facility agriculture engineering, based on multi-source data fusion, intelligent early warning for facility agriculture energy internet can be used to prevent agricultural meteorological disasters, broadening avenues for technology cooperation in various regions of the world to achieve greater agricultural carbon reduction goals. More importantly, it helps maintain global food security, eliminate hunger, and reduce economic inequality.

Funding

This research received no external funding.

Acknowledgments

We appreciated the help of Ms Wang Ruoni at Jiangsu University of Science and Technology for the use of the software.

Conflicts of Interest

The authors declare no conflicts of interest.

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