frontiers | Frontiers in Environmental Science

TYPE Review
PUBLISHED 17 October 2023
DOI 10.3389/fenvs.2023.1268432

OPEN ACCESS

EDITED BY
Zhen Liu,
Nanjing Normal University, China

REVIEWED BY
Xianjun Li,
Chinese Academy of Social Sciences (CASS), China
Muhammad Ziaul Hoque,
Bangabandhu Sheikh Mujibur Rahman Agricultural University, Bangladesh
Shijiu Yin,
Qufu Normal University, China

*CORRESPONDENCE
Gang Zhou,
zhougang@ouc.edu.cn

†These authors have contributed equally to this work and share first authorship

RECEIVED 28 July 2023
ACCEPTED 03 October 2023
PUBLISHED 17 October 2023

CITATION
Jin W, Wu S, Zhang Y, Zhou G, Xu L and Xu Y (2023), Review on Chinese agricultural science and technology research from a low-carbon economy perspective: hotspots, evolution, and frontiers.
Front. Environ. Sci. 11:1268432.
doi: 10.3389/fenvs.2023.1268432

Review on Chinese agricultural science and technology research from a low-carbon economy perspective: hotspots, evolution, and frontiers

Weibo Jin[1,2†], Shiping Wu[1], Yi Zhang[1†], Gang Zhou[3*], Lijie Xu[1] and Yao Xu[1]

[1]Business School, Qingdao University of Technology, Qingdao, China, [2]Institute of Marine Development, Ocean University of China, Qingdao, China, [3]School of Economics, Ocean University of China, Qingdao, China

Against the background of global climate change, agricultural science and technology play a vital role in achieving a low-carbon economy and sustainable development. Based on the research data of agricultural science and technology in Web of Science and China National Knowledge Infrastructure, adopting the bibliometric method, a knowledge graph was drawn using CiteSpace software; this paper analyzes the hotspot distribution, structural relationship and evolution process context while also comparing the difference between China and abroad from 1998 to 2023. The results indicate that existing research is mainly distributed in the following core modules, namely, agricultural science and technology, industrialization, modern agriculture, low-carbon agriculture, *etc.* The evolution of the research context features three stages: the traditional agricultural, current agricultural, and high-quality agricultural stages respectively. Research in China and abroad demonstrates both overlaps and differences in terms of knowledge structure, and such differences are related mainly to the concept of low-carbon agriculture, a variety of research perspectives, and the agricultural science and technology system. To expand the knowledge structure, deepening the research on, respectively, the evaluation and measurement of agrarian carbon footprint, micro-production entities, and strengthening international agricultural science and technology cooperation are innovative directions for future studies. This article systematically reviews agricultural scientific research from the perspective of a low-carbon economy, providing a reference point for the green and low-carbon transformation of agriculture in every country.

KEYWORDS

agricultural science and technology, low-carbon economy, green development, research hotspots, evolution

1 Introduction

As social productivity continues to advance and the population keeps increasing, humans are causing unprecedented damage to the natural ecological environment (Ahmed et al., 2021). In the face of an increasingly deteriorated ecological environment, how to effectively coordinate the relationship between economic and social development and ecological protection has become a major issue of global concern (Scharlemann et al., 2020). Faced with the challenges of high resource consumption and severe environmental costs in the current food system (Cheng et al., 2023), the leaders of many countries have expressed their vision for achieving sustainable development. The United Nations also considers agriculture an important component of Sustainable Development Goals (SDGs), making agricultural sustainability a major global initiative (Warchold et al., 2020). Low-carbon agriculture is an important path to promote agricultural sustainability, as it can efficiently produce raw materials, food, feed, and fiber while reducing energy input and greenhouse gas emissions in agriculture (Piwowar, 2019), thereby playing a crucial role in achieving the goals of carbon peaking and neutrality respectively.

Food security and agricultural sustainability are fundamental issues related to human survival, and low-carbon agriculture plays an important role in addressing them. The Chinese government has always considered solving the food problem a top governance priority. According to the "Statistical Yearbook of World Food and Agriculture 2022" released by the Food and Agriculture Organization of the United Nations, China (75 million hectares) has the largest irrigated area in the world. China ranks first globally in producing crops such as wheat, rice, and potatoes, as well as agricultural products such as pork, eggs, and fish. However, due to China's large population base, high consumption of agricultural and sideline products, imperfect alternative technologies for fertilizers, and a large volume of greenhouse gas emissions from animal husbandry, China's agricultural carbon emissions have been continuously increasing. The Chinese government has attached ever more importance to carbon emissions in recent years. In 2021, the government put forward the requirement of "accelerating green development in agriculture and promoting carbon sequestration and efficiency improvement in agriculture" in the "Opinions on Fully Implementing the New Development Concept to Achieve Carbon Peak and Carbon Neutrality," raising the necessity and importance of low-carbon agricultural development to a new level. In 2023, further emphasis was placed on "comprehensively and deeply promoting green development in agriculture and constructing an agricultural powerhouse" in the "Opinions on Promoting Key Work of Comprehensive Rural Revitalization in 2023". Thanks to the government's emphasis on green and low-carbon agricultural development, China's total agricultural carbon emissions have remained stable at 7%–8% since 2012, showing a significant downward trend in recent years. The development of low-carbon agriculture mainly relies on agricultural technological innovation (Chen Q. et al., 2016). Therefore, this research reviews agricultural technology-related literature to provide a reference for other agricultural countries to develop low-carbon agriculture and achieve SDGs.

Previous studies have extensively researched the Chinese agricultural technology-related literature (Lai et al., 2019; Wang J. et al., 2022; Zhang et al., 2023). However, these studies are limited to either the China National Knowledge Infrastructure (CNKI) or the Web of Science (WOS) databases respectively, lacking a comprehensive perspective that combines both in terms of analysis and comparison. In addition, unlike previous studies (Chen Y. et al., 2016), this research adopts a low-carbon economic perspective. It focuses on analyzing the research dynamics and trends of Chinese agricultural technology research in low-carbon agriculture, aiming to lay a foundation for future research and outline possible innovative directions. This research addresses the following questions: 1) analyze the characteristics of agricultural technology research; 2) study the distribution of hotspots in agricultural technology research; 3) sort out the context of Chinese agricultural technology research; 4) compare the differences between Chinese and international agricultural technology research; 5) explore the future trends of agricultural technology research, all five questions being based on a low-carbon economic perspective. Therefore, this research utilizes the CNKI and WOS core databases to analyze agriculture-related literature. It employs Citespace software to conduct a systematic bibliometric visualization of Chinese agricultural technology research from a low-carbon economic perspective, comparing it with international agricultural technology research.

2 Methods and data sources

2.1 Research methods

Bibliometrics, initially proposed by British information scientist Alan Pritchard in 1969, is a research method used to quantitatively analyze literature information. As one of the fundamental research areas of bibliometrics, bibliometric analysis methods–including statistical, citation, mathematical modeling, and co-citation analysis, respectively–have gradually formed a core method system that has been explored on a continuous basis by scholars (Glänzel, 2015). It has been widely applied in publication statistics, academic hotspot tracking, and future research directions in various fields (Zhao and Xu, 2010), which has contributed significantly to the development of information visualization. Information visualization, proposed by Robertson et al., in 1989, is a computer-based method for the visual analysis of abstract data. It reveals the development trends, hotspots, and frontiers of scientific research through dynamic graphics (Bederson and Shneiderman, 2004). Therefore, information visualization assists scholars in quickly understanding and predicting the boundaries and dynamics of scientific research, thereby exploring new research areas that feature complex scientific information (Chen, 2006). With the advancement of information technology and scientometrics, information visualization techniques have been increasingly applied to literature information mining. In terms of mainstream information visualization analysis software, Citespace software integrates various analysis functions such as knowledge clustering, multivariate statistics, and co-cited literature, effectively combining traditional bibliometrics with information visualization. It significantly impacts information analysis and is one of the mainstream visualization analysis software tools currently available (Zhang et al., 2019).

2.2 Data sources and overview

This study uses the CNKI and WOS databases as data sources to ensure the original data's comprehensiveness, accuracy, and

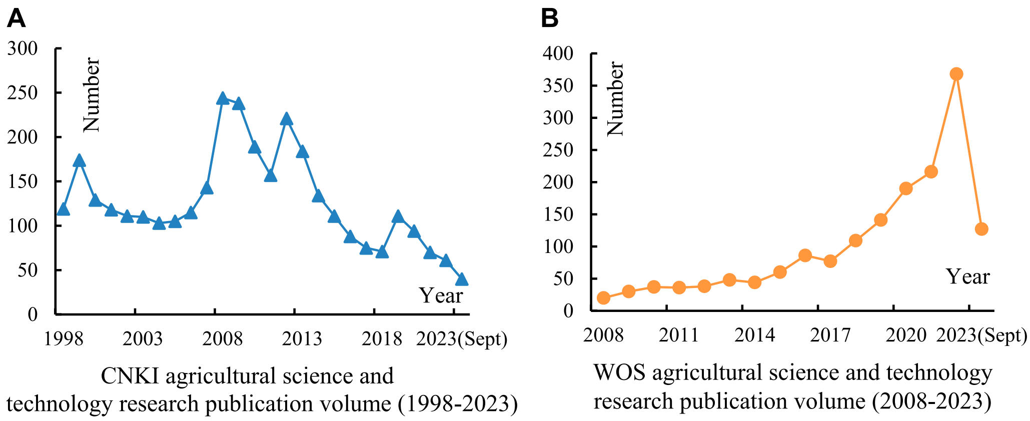

FIGURE 1
Annual publication volume of agricultural science and technology research (note: data from CNKI and WOS).

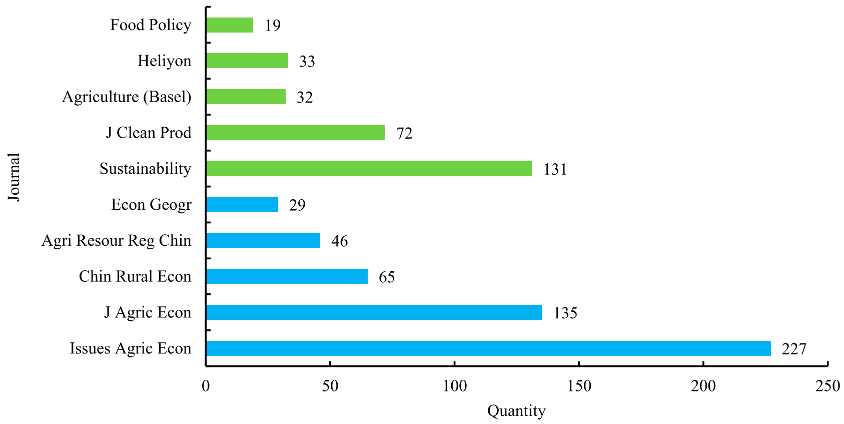

FIGURE 2
Distribution of major journals for agricultural science and technology research publications.

representativeness. The CNKI database selected Chinese Social Sciences Citation Index (CSSCI) journal articles as the primary data, with the search condition based on the subject “agricultural science and technology” with the search period spanning from 1998 to 2023. Non-research articles such as news reports and conference summaries were excluded, resulting in 3,315 relevant articles. The WOS core database selected the Science Citation Index (SCI) and Social Science Citation Index (SSCI) and set the search topic as “agricultural science and technology”. The search period was from 2008 to 2023, the language was English, and the document types were articles and reviews. Duplicate articles were removed to ensure the validity of the data, resulting in a total of 1,627 literature records. All literature was downloaded on 4 September 2023. Figure 1 illustrates the distribution of agricultural science and technology publications.

Based on Figure 1, it can be observed that the annual publication volume of agricultural science and technology research showed an initial increase followed by a subsequent decrease between 1998 and 2023 in the CNKI database, while in the WOS database, the growth trend was more significant. The period from 1998 to 2005 represented a stable development phase for agricultural science and technology research in China. Subsequently, there was a continuous increase in research publication volume, with fluctuations observed from 2006 to 2012. In 2008, the annual research publication volume peaked at 244 articles. From 2013 to 2023, there was a fluctuating downward trend in research publication volume, indicating a stabilization of research in Chinese agricultural science and technology. In the international context, the research publication volume of international agricultural science and technology showed a slow growth from 2008 to 2017, followed by a substantial increase from 2018 onwards, indicating sustained attention from international scholars in this field. Analyzing the journal distribution in Figure 2, the top five journals in research publication volume in international agricultural science and technology research are Food Policy, Heliyon, Agriculture-BASEL, Journal of Cleaner Production, and Sustainability. In contrast, the top journals in Chinese agricultural science and technology research are Economic Geography, Chinese Agricultural Resources and Regional Planning, Chinese Rural Economy, Agricultural Techno-Economics, and Agricultural Economic Issues.

TABLE 1 Core hotspot keywords.

Particular year	Keywords	Frequency/ Section	Centrality	Particular year	Keywords	Frequency/ Section	Centrality
1998	Agriculture	222	0.28	2004	Modern agriculture	123	0.11
1998	Agricultural science and technology	177	0.28	2004	Agricultural enterprise	10	0.01
1998	Industrialization	46	0.05	2004	Human resources	6	0.01
1998	Productivity	11	0.02	2007	Influencing factor	69	0.08
1998	Promoting agriculture by applying science and technology	20	0.01	2008	Science and technology support	8	0.01
1999	Scientific and technological innovation	78	0.10	2011	Low-carbon agriculture	31	0.03
1999	Sustained development	5	0.01	2011	Low-carbon economy	5	0.01
2000	Agricultural technology extension	9	0.01	2013	Professional farmers	2	0.01
2001	Farmer income increase	36	0.03	2016	Collaborative innovation	9	0.01
2004	Food security	28	0.02	2018	Rural revitalization	47	0.06

TABLE 2 Three major sectors of agricultural technology supporting a low-carbon economy.

Serial number	Cluster	Embodiment	Factors affecting carbon emissions	Rationale
1	#2 farmer income increase, #3 environmental pollution, #5 agricultural productivity, #11 food security	High energy consumption, high emissions, high pollution traditional agricultural production, resulting in rapid growth of agricultural carbon emissions	Economic factors: level of economic development	The Environmental Kuznets Curve
2	#4 industrialization, #6 modern agriculture, #7 technology transfer, #8 resource management	With the adjustment of agricultural industrial structure, the improvement of technology transfer efficiency and the improvement of industrialization level, the optimization of resource utilization efficiency has become an inevitable requirement for the development of low carbon agriculture	Institutional factors: resource utilization efficiency	The theory of recycling economy
3	#0 agricultural technology, #1 high-quality development, #9 technology information, #10 low-carbon agriculture	Relying on digital empowerment, building a low-carbon, safe and efficient development of agricultural science and technology system, accelerating the low-carbon transformation of agriculture	Technical factors: agricultural technology progress and promotion	Sustainable development theory

3 Research hotspot distribution

Keywords are highly summarized descriptions of the core research topics in literature. The co-occurrence relationship and connection strength of keywords are essential bases for analyzing the distribution of research hotspots in literature. This study adopts a 1 year time slice and uses the Pathfinder and Pruning of the Merged Network to conduct hotspot evolution analysis and draw a clustering map of agricultural science and technology research in China (Li and Sun, 2014).

3.1 Hotspot keyword analysis

Table 1 reflects the evolution of the leading research hotspots and topics in agricultural science and technology in China from 1998 to 2023 from the perspective of the low-carbon economy. Keywords such as agricultural science and technology, industrialization, modern agriculture, low-carbon agriculture, and rural revitalization have high co-occurrence frequencies, reflecting the core hotspots of agricultural science and technology research in China from 1998 to 2023. From the perspective of co-occurrence

TABLE 3 Agricultural carbon footprint evaluation index.

Object	Calculating method	Merits and Demerits	Reference
Agricultural carbon emissions	IPCC	It is widely accepted and applied, with high scientificity and comparability, but it can not reflect the whole picture of carbon emission in the production process of agricultural system	Chen et al., 2019; Li D. et al., 2022; Xiao X. et al., 2022
	life cycle approach	It can reflect the impact of the whole process of agricultural products from production to abandonment on the environment, but it has strong subjectivity in the delineation of different cycle boundaries, which can easily cause measurement errors	Huang W. et al., 2022; Yu et al., 2023
	Input-output method	It can fully reflect the carbon emission of each input factor in the process of agricultural production, but the amount of data required is huge, the calculation process is complex, and the input-output table is discontinuous	Yu et al., 2020; Jiang et al., 2022
	Carbon emission coefficient method	The actual carbon emission data can be obtained directly, and the results are open and transparent, but there are uncertainties due to data quality and assumptions	Cui et al. (2014)
Agricultural carbon sinks	Plant-based carbon sequestration	The effects of different crop varieties, planting density, fertilization management and other factors on carbon sink capacity can be evaluated, but the calculation process is susceptible to climatic conditions and other factors	Wang J. et al., 2022; Bamière et al., 2022
	Soil carbon sequestration	Soil carbon sequestration capacity can be assessed throughout the planting cycle, but the assessment of soil carbon sequestration capacity is affected by factors such as soil sampling, sample treatment and analysis	Li et al., 2021; Winkler et al., 2023
Agricultural carbon emission efficiency	Univariate calculation	It can directly reflect the carbon emission efficiency in the process of agricultural production, but ignores the economic benefits of agricultural production and other production environment impacts	Pang et al. (2020)
	SFA	The technical efficiency and allocation efficiency in the process of agricultural production can be understood, but the reliability of the model estimation results depends on the setting of the function form	Zhu et al. (2021)
	DEA	It is suitable for a variety of input-output combinations, but it cannot directly judge the technical efficiency and allocation efficiency in the production process	Shan et al. (2022)

relationships, the above keyword nodes are closely connected with high co-occurrence intensity, forming clusters of hotspots in the field of publication.

In the early stage of research, the essential keywords focused on carbon emissions caused by the single agricultural production mode in China. In this stage, traditional agriculture dominated and exhibited characteristics such as low efficiency, high energy consumption, and high pollution, resulting in increasing pressures on resources and the environment and significant agricultural carbon emissions. To gradually achieve the transformation and upgrading of agricultural production from quantity to quality while solving the problems of low quality and low efficiency in agricultural production, it is necessary to accelerate the improvement of agricultural production efficiency, enhance the quality of farm products, optimize the utilization of energy resources, construct a resource-saving and environmentally friendly agricultural production model, and realize the transformation and upgrading from traditional agriculture to modern agriculture. In the mid-term phase of the research, the essential keywords mainly focused on carbon emissions caused by extensive agricultural production methods. Due to the lack of an established modern agricultural industry system with automation, intelligence, and informatization, weak agricultural infrastructure, lagging industrial development, and the absence of core competitiveness, China's agricultural development still relies on an extensive mode that pursues production and speed unilaterally. This single agricultural production mode involves measures such as excessive use of fertilizers and pesticides, unreasonable land use and mechanized operations, leading to aggravated carbon emissions. Building on the technology and innovation-driven modern agricultural industry systems became the focus of this stage of the research. In the later stage of the study, the essential keywords mainly focused on building a low-carbon agricultural system through collaborative agrarian production methods. Technological innovation in agriculture is the key to promoting the coordinated development of farm production and the ecological environment. By using digital means to reconstruct traditional agricultural production methods and industrial operation models, the research aims to effectively make up for the shortcomings of agricultural modernization and form a complete system for green, safe, and low-carbon development in agriculture.

3.2 Keyword cluster map analysis

Based on the keyword clustering information in Figure 3, the 11 main keywords can be categorized into three clusters that support a low-carbon economy in agricultural technology (as show in Table 2).

The first cluster mainly includes #2 farmer income increase, #3 environmental pollution, #5 agricultural productivity, and #11 food security. Low levels of farmer income, extensive agrarian production methods, and intense agricultural productivity lead to problems such as high energy consumption,

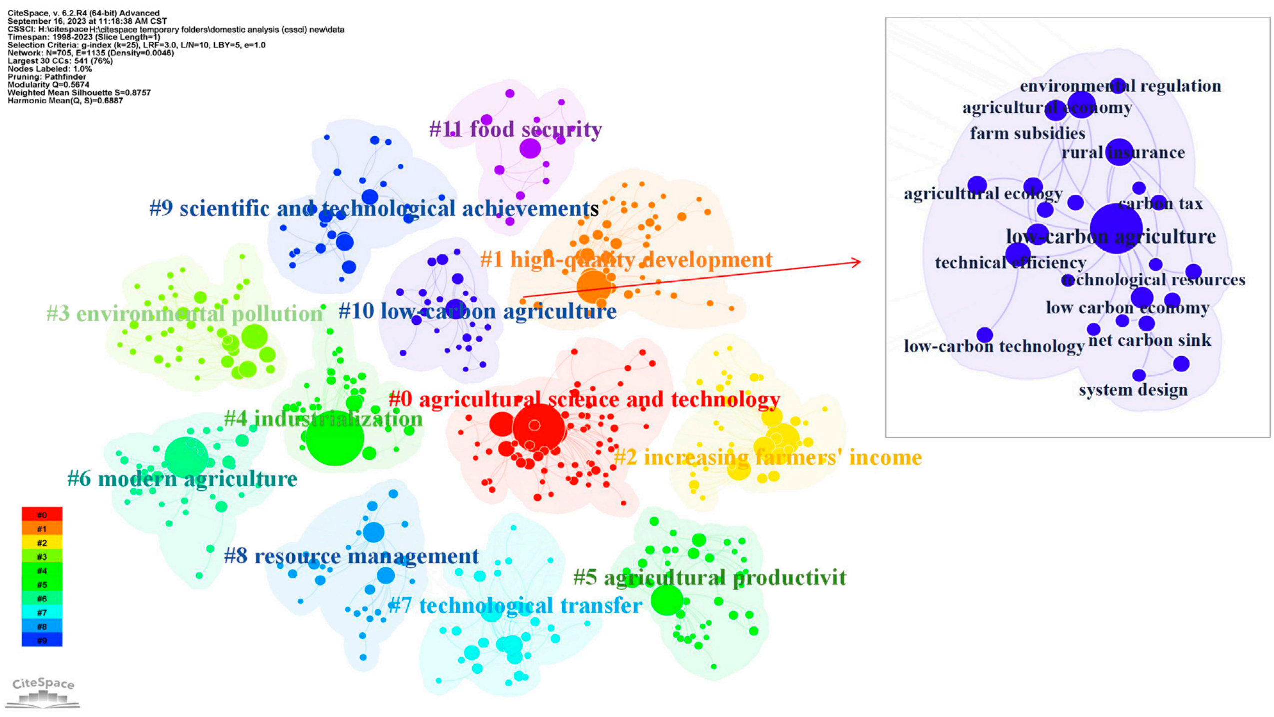

FIGURE 3
Co-occurrence network clustering diagram of keywords.

emissions, and pollution levels in agricultural production respectively. This results in a continuous increase in agricultural carbon emissions and prominent environmental pollution issues, which in turn reduces farm output and, to some extent, affects food security. The Environmental Kuznets Curve can effectively explain the low-carbon development of agriculture in this stage, where agricultural economic development and carbon emissions are at the pre-turning point of the "inverted U" shape. As agricultural economic development drives the improvement of agricultural production efficiency, there is also an "inverted U" relationship between agricultural production efficiency and agrarian carbon emissions. In regions with lower agricultural production efficiency, improving production efficiency significantly increases carbon emission intensity, whereas in areas with higher agricultural production efficiency, improving production efficiency effectively suppresses carbon emission intensity (Zhu and Huo, 2022). On the other hand, agricultural economic development is accompanied by an increase in people's income levels, which stimulates the desire for improved quality of life and leads to active consumption of green and low-carbon agricultural products, thereby driving the transformation of agriculture towards low-carbon practices (Yuzhen, 2021).

The second cluster mainly includes #4 industrialization, #6 modern agriculture, #7 technology transfer, and #8 resource management. With the adjustment of agricultural industrial structure, the efficiency of technology transfer continues to improve while the level of industrialization continues to increase. Optimizing resource utilization efficiency becomes an inevitable requirement for the development of low-carbon agriculture. On the one hand, the transformation and upgrading of agricultural industrial structures is a critical means to reduce agricultural carbon emissions. Different agricultural sectors have varying degrees of impact on carbon emissions, with crop farming and livestock farming being the primary sources of agricultural carbon emissions (Dong, 2016). Crop farming involves the use of high energy-consuming machinery and agrochemicals, while livestock production and manure discharge generate large amounts of greenhouse gases (Dai et al., 2021). On the other hand, compared to some agricultural countries limited by knowledge reserves and research and development investment, frequent low-carbon technology transfer between agricultural powerhouses has demonstrated significant carbon reduction effects. Therefore, promoting global sharing of low-carbon agricultural technologies can effectively address climate change issues and mitigate the global warming trend (Gu et al., 2020).

The third cluster mainly includes #0 agricultural technology, #1 high-quality development, #9 technology information, and #10 low-carbon agriculture. Agricultural technological innovation is the key to driving the transformation and upgrading of agricultural industrial structures. By further optimizing agricultural technology information and accelerating the empowerment of new technologies and methods in agricultural production, extensive and traditional agricultural production methods can be changed, further reducing the level of agricultural carbon emissions, thereby achieving high-quality development of low-carbon agriculture. In the era of digital economy, digital technology, as a new production factor, can effectively break through the information isolation faced by farmers while promoting low-carbon agricultural technologies (Huang W. et al., 2022). With the continuous development of

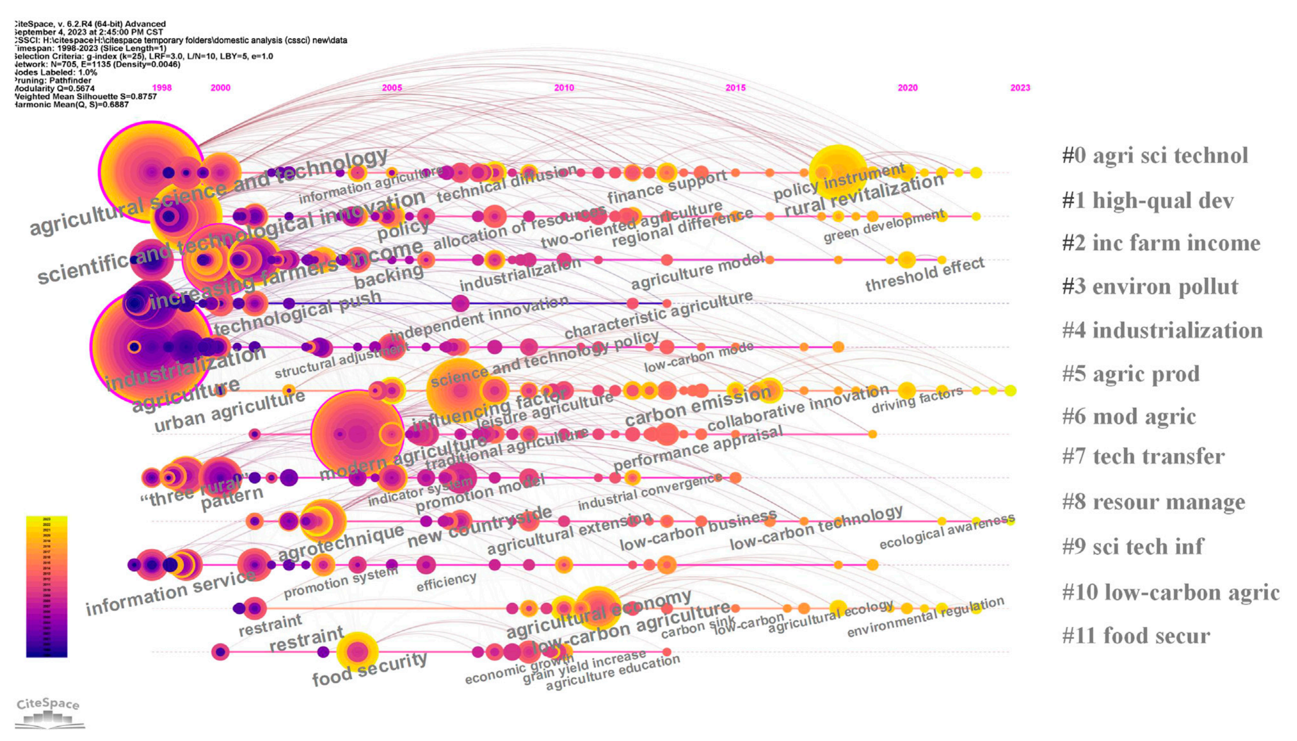

FIGURE 4
Keyword co-occurrence network timeline diagram.

digital technology, the "digitalization and decarbonization" development model has become the only path for the development of low-carbon agriculture (Tian, 2023). Promoting agricultural digitization can help replace traditional agricultural production methods by improving human capital, social capital, and digital finance levels, providing economies of scale, economic aggregation effects, and innovation effects for agricultural production. This will help to build a low-carbon, safe, and efficient agricultural technology system (Huang and Nie, 2023) and achieve high-quality development in agriculture.

4 The evolution of agricultural science and technology research

The evolution of research paradigms in the thematic field is primarily reflected in the temporal changes in research content, perspectives, and methodologies. Firstly, the keyword co-occurrence network timeline graph mainly depicts the historical evolution relationship between different clusters, illustrating the evolving trends of various hot topics within the field over time. In the timeline graph, the temporal distribution of nodes represents the first occurrence of keywords in the overall research publications, while the node size reflects the accumulated co-occurrence frequency of the keyword nodes in the research publications. Therefore, by constructing the keyword timeline graph, it is possible to summarize the variations in hot topics in agricultural science and technology research. Secondly, in the literature co-citation network, highly central nodes often represent influential or representative research works, and their research content, perspectives, and methodologies serve as essential references for analyzing the research evolution of the thematic field. Therefore, based on the keyword timeline graph and high-centrality literature from different periods, the research trajectory of agricultural science and technology achievements from 1998 to 2023 can be organized. As shown in Figure 4, the keyword timeline view combined with the evolution of clusters and keywords is utilized to divide the research process of Chinese agricultural science and technology into stages. Overall, the development of agricultural science and technology-related research can be divided into three phases, each characterized by specific differences in research themes, perspectives, and methodologies.

4.1 Development stages of traditional agriculture

The starting phase of agricultural science and technology research in China was from 1998 to 2003. The distribution of keywords during this period reveals a focus on issues such as industrialization, technological innovation, productivity, and farmers' income. In the early stage, China's agricultural output was relatively low. Due to factors such as a large population base and rapid population growth, there was a continuous increase in the demand for grain production in China. In particular, after the Chinese government officially proposed the concept of "food security", there was an urgent need to improve agricultural production methods, enhance the supply level of Chinese agricultural products, thereby ensuring food security. Therefore, research during this stage primarily revolved around the issue of increasing agricultural product yields. For instance, Yang et al. (2017) and many other scholars found through their research that agricultural technological progress significantly improves grain production, whereas resource wastage and excessive use of fertilizers in agriculture lead to ecological damage to agricultural resources and the environment (Zhang and Nian, 2004; Zhang, 2020). In terms of production subjects, Xiang et al. (2012) pointed out that a lack of relevant knowledge among farmers is the reason for the inefficient utilization of agricultural resources, while Zhou and Li (2021) has argued that the cooperative modes among farmers hinder the improvement of agricultural resource utilization efficiency, while vertical cooperation can help address issues related to the harmful effects of fertilizers, pesticides, and other factors on the agricultural ecological environment. Overall, the development of the agricultural industry in China faces challenges such as limited land resources, severe water shortages, predominant small-scale farming practices, as well as significant pollution from fertilizers and pesticides. Consequently, the research focus has shifted towards constructing a system and framework for sustainable agricultural development.

4.2 Development stages of modern agriculture

With the proposal of China's agricultural modernization strategy, exploring the path of agricultural modernization with Chinese characteristics has become a research hotspot during this period. It is mainly reflected in the following aspects: interpretation from the perspective of transformation of development modes suggests the optimization of agricultural industrial structure (Yang, 2004; Zu, 2007); adjustment of management systems (Wang, 2007); improvement of economic efficiency (Zhu and Dong, 2013); and the transformation of industrial value chain from low to high, extensive to intensive, and from high energy consumption and pollution to energy-saving and environmentally friendly practices (Li, 2010). In terms of elaborating on the issue of agricultural specialization and division of labor, Yang et al. (2011), for example, argued that accelerating the construction of new agricultural social service organizations helps meet the needs of modern agricultural development. Xi (2007) has suggested that the integrated development of agricultural industries can promote the improvement of comprehensive agricultural benefits while helping to realize agricultural multifunctionality. Jiang (2011) examines the importance of accelerating the reform of public agricultural service institutions and highlighting the need for the construction of comprehensive modern agricultural service platforms. Research on the role of agricultural support policies suggests that deepening agricultural technological innovation policies while focusing on seed industry support, such as the implementation of preferential support policies for the seed industry, is crucial for seed industry revitalization (Li and Huo, 2008). Emphasizing agricultural equipment policies, support delivered through machinery subsidies significantly improves agricultural production efficiency (Wang and Xiao, 2007). Additionally, by concentrating on outsourcing and hosting agricultural service policies, outsourcing services in agricultural production processes can effectively enhance technology utilization efficiency and promote grain production (Zhao et al., 2013).

4.3 Development stage of high-quality agriculture

With the proposal of China's rural revitalization strategy, scholars have increasingly emphasized the importance of high-quality agricultural development, mainly focusing on the significance of low-carbon agriculture. The analysis of the keyword co-occurrence network timeline indicates that keywords such as low-carbon economy, collaborative innovation, dual-type agriculture, and environmental regulations have become frequently co-occurring nodes. Low-carbon agriculture is an essential approach to achieving high-quality agricultural development, in an attempt to ensure national food security and sustainable food supply while promoting agricultural development with high energy efficiency, low energy consumption, and low carbon emissions. Agricultural technology plays a crucial role in facilitating low-carbon agriculture. China emphasizes the establishment of a low-carbon agricultural system characterized by source control as a priority, consumption reduction as the main focus, carbon sink augmentation as a supplementary measure, and circular utilization. This system aims to enhance the efficiency of agricultural resource utilization and promote agricultural production featuring high efficiency, low energy consumption, low carbon emissions, and high carbon sequestration (Li D. et al., 2022). In terms of source control, goals for emission reduction can be achieved through developing high-yielding, low-emission, water-saving, drought-resistant, and high-quality wheat varieties, utilizing new types of green, efficient, environmentally friendly, and high-quality fertilizers, as well as promoting low-carbon, low-energy-consumption and low-pollution poultry farming technologies (Cheng and Yao, 2022; Samoraj et al., 2022; Zeleke et al., 2022). Consumption reduction can be achieved by employing technologies such as big data, artificial intelligence, and the Internet of Things to monitor meteorological conditions, soil moisture, crop growth, and other parameters, thereby enabling exemplary management of agricultural production and efficient resource utilization (Zhang et al., 2022). Carbon sink augmentation involves measures such as no-tillage farming, straw returning, and green manure application, which can increase soil organic matter content. The promotion of conservation tillage techniques helps reduce soil organic matter depletion. Comprehensive land consolidation supports the achievement of emission reduction and carbon sink augmentation goals (Liao et al., 2022; Zhuang et al., 2023). Regarding circular utilization, constructing a technological support system for an agricultural circular economy enables the resource utilization of livestock and poultry manure, crop straw, and by-products. Additionally, such a technological support system explores the carbon sequestration potential and economic benefits of agricultural biomasses (Yang et al., 2022).

5 Differences between Chinese and international research

In the early stages of international agricultural technology research, attention was focused on food security issues, gradually shifting towards ecological issues while, more recently, greater attention has been paid to low-carbon issues. The evolution of relevant research in China is similar. In the early stages of research, most studies pointed out that the development of agricultural technology is a crucial response to food security issues, such as the promotion of improved crop varieties, the use of fertilizers and chemical pesticides, and the transformation towards agricultural mechanization, which can significantly improve agricultural productivity and effectively address food security issues (Abah et al., 2010; Sinyolo, 2020; Spanaki et al., 2021). The relationship between agricultural technology and food security is a complex one, and output indices cannot be the sole focus (Magrini and Vigani, 2016). With the development of information, communication, and automation technologies respectively, scholars have begun to explore the application of agricultural technology to enable the high-quality development of low-carbon agriculture (Liu et al., 2020).

5.1 Different perspectives on the concept of low carbon agriculture

Existing research relies on low-carbon agricultural economic theory to explain the connotations of low-carbon agriculture based on a relatively broad understanding of the essence of low-carbon agriculture. International studies, due to their earlier development, actively promote interdisciplinary exchanges in economics, management, politics, and other fields, aiming to grasp the essence of the concept of low-carbon agriculture. The concept of a "low-carbon agricultural economy" in China was first proposed by Wang (2008), who defined it as an economy that minimizes carbon emissions and maximizes social benefits under existing technologies. Weng et al. (2009) believe that low-carbon agriculture is consistent with the concept of circular agriculture, both of which possess characteristics such as low energy consumption, sustainability, and a systemic approach. Liu et al. (2012), building on theoretical economics, emphasize the need for a comprehensive consideration of the relationship between economics, society, and ecology in low-carbon agriculture to achieve sustainable agricultural development. Chinese scholars' understanding of the concept of low-carbon agriculture is gradually evolving and has yet to reflect a unified definition. Internationally, the concept of "low-carbon agriculture" can be traced back to the Energy White Paper published by the British government in 2003. Subsequently, Pimentel, based on interdisciplinary theories and research achievements in ecology and management, proposed the concept of input reduction development, which drew significant attention to low-carbon agriculture. Knudsen et al. (2014), combining theories from management and political science, have argued that the development of low-carbon agriculture involves issues such as technological design, institutions and systems, require the state to formulate corresponding policies to promote the transformation of an appropriate agricultural industry structure.

5.2 Different research perspectives in agricultural science and technology

In Chinese agricultural science and technology research, there is a predominant focus on macro-level empirical studies, while international studies tend to examine production entities such as agricultural enterprises, family farms, and individual farmers, emphasizing micro-level analysis. Chinese studies often utilize regional data for their empirical analysis of agricultural carbon emissions characteristics and influencing factors, as well as performance evaluation of low-carbon agricultural development (Xiao X. et al., 2022; Lu et al., 2023). Alternatively, qualitative analyses are conducted on policy evaluations and improvement recommendations related to initiatives such as "energy conservation and emission reduction" and "low-carbon city" pilots (Che, 2022; Jiang and Jiang, 2023), with relatively less attention devoted to micro-level production entities in Chinese agriculture. On the other hand, international agricultural science and technology research mainly focuses on studying micro-level production entities, such as farmers' adoption of improved rice technologies (Ambali et al., 2021), farm utilization of automated milking systems (Schewe and Stuart, 2015), and collaborations between enterprises and universities for innovation (Luo et al., 2022). These studies contribute to a fundamental exploration of relevant influencing factors and the resolution of practical issues.

5.3 Different research on the agricultural science and technology system

The agricultural science and technology system in China is still in need of improvement, while the international agricultural science and technology system is relatively mature. The Chinese agricultural science and technology system mainly includes the construction of agricultural technology networks and an innovation system for agricultural technology. The former consists of universities and research institutes, technology extension organizations, and technology transfer entities. The latter is led by the government and supported by institutional encouragement and constraint mechanisms, promoting technological innovation, development, and the dissemination and application of low-carbon technologies (Sun and Cheng, 2021). Currently, the Chinese agricultural science and technology innovation system still faces challenges such as decentralized organizational management of innovation entities, low efficiency in the transformation of scientific and technological achievements, and insufficient investment in agricultural enterprise innovation, indicating that the innovation system still needs improvement (Li and Mao, 2021).

In contrast, the agricultural science and technology innovation system in the United States is based on universities, establishing an integrated system of agricultural research, education, and promotion. The land-grant colleges in each state apply a large number of advanced technologies to agriculture every year, including energy-saving and carbon-reducing technologies, providing solid technical support for the development of low-carbon agriculture in the United States (Zapata-Cantú and Gonzalez, 2021). The agricultural innovation system in South Korea is government-led, emphasizing high investment in agricultural technological innovation, coordination between policies and laws, and a close connection between technology innovation projects and field applications. These measures have effectively facilitated South Korea's progress in becoming a leading agricultural technology country (Zhou et al., 2021). In comparison, the agricultural science and technology systems of agricultural powerhouses are more mature.

6 Research trends in agricultural science and technology

The new generation of ubiquitous information technologies, such as smart agriculture, artificial intelligence, and agriculture 4.0, represent breakthrough applications in the field of agriculture. The dissemination and application of these technologies will bring about comprehensive changes in core technological advances, collaborative research and development innovation, and production organization modes in agriculture. With the continuous advancement of technological innovation, their core driving role in the development of low-carbon agriculture is becoming increasingly prominent (Li and Li, 2020). Against this backdrop, it is critical to grasp the role of the technological support system, performance evaluation indicators, and economic development models of low-carbon agriculture. Through the induction and sorting of the structural relationships and trends of China's agricultural science and technology research hotspots from 1998 to 2023 and by comparing these with international research, this study reveals the following trends in future agricultural science and technology research.

6.1 Constructing the evaluation index system of an agricultural carbon footprint

Based on existing research, the agricultural carbon footprint assessment index system faces issues such as inconsistent accounting parameters and incomplete reference elements (Zhang and He, 2022). Current assessments mainly revolve around agricultural carbon emissions, agricultural carbon sinks, and agricultural carbon emission efficiency, with a corresponding calculation system being established (Tian and Yin, 2022) (as show in Table 3).

The main methods for calculating agricultural carbon emissions include the IPCC (Intergovernmental Panel on Climate Change), input-output, life cycle assessment, and field measurement methods respectively. However, each method has its limitations. The IPCC method mainly utilizes relevant coefficients and macroeconomic data to measure agricultural carbon emissions but needs to comprehensively reflect the carbon emissions throughout the entire agricultural production process (Chen et al., 2019; Li J. et al., 2022; Xiao P. et al., 2022). The input-output method mainly converts factors influencing the agricultural production environment into economic benefits for measurement purposes, but this method requires a high quantity and quality of data (Yu et al., 2020; Jiang et al., 2022). The life cycle assessment method primarily measures the environmental impact of agricultural products throughout their entire production process, but subjective issues arise in determining life cycle boundaries (Huang X. et al., 2022; Yu et al., 2023). The emission factor method directly calculates the carbon dioxide equivalent generated during the entire life cycle of agricultural products. However, it is subject to uncertainty due to data quality and assumptions (Cui et al., 2014).

Regarding methods for calculating agricultural carbon sinks, there are two main types: crop carbon sink and soil carbon sink. The crop carbon sink method calculates the total carbon sink of crops through water content and carbon absorption rate, but it is easily affected by climatic conditions (Bamière et al., 2022; Wang Y. et al., 2022). The soil carbon sink method is based on detecting soil organic carbon content and can establish models that predict soil carbon sequestration capacity, but external factors can also influence it (Li et al., 2021; Winkler et al., 2023).

Regarding methods for calculating agricultural carbon emission efficiency, there are two main types: single-factor approach and multi-factor approach. The single-factor approach commonly uses carbon emission intensity to reflect carbon emission efficiency intuitively but neglects economic benefits (Pang et al., 2020). The multi-factor approach includes stochastic frontier and data envelopment analysis respectively. The stochastic frontier analysis incorporates agricultural carbon emissions as input factors for measurement, but the estimation results of the model are influenced by the functional form chosen (Zhu et al., 2021). Data envelopment analysis treats agricultural carbon emissions and carbon sinks as undesirable outputs and can be applied to various input-output combinations. However, it cannot distinguish between technical efficiency and allocative efficiency during the production process (Shan et al., 2022).

6.2 Increasing the research on micro-production subjects

At present, academic research on low-carbon agriculture mainly focuses on large-scale farming households, with relatively less research on small farming households. However, small farming households play a significant role in China's agricultural production. Therefore, in the pursuit of the "double carbon" goal of agricultural development, the importance of small farming households cannot be ignored, and research on their role in low-carbon agriculture development should be strengthened. Farming households of different scales have varying investment and operating capabilities. When small farming households transition from production to low-carbon operations, they tend to prefer labor-intensive low-carbon technologies based on low-risk preferences with limited economic benefits (Zhao and Zhou, 2021). In addition, it is difficult to measure the carbon emissions of small farming household production processes, which limits their ability to participate in carbon market transactions and receive effective incentives from carbon emission trading rights policies. The generally lower education level of small farming households makes it challenging for them to learn and apply low-carbon agriculture technology (Guo et al., 2015). Despite many issues, rapid development in agricultural technology allows for specialized division of labor in agricultural production processes. Small farming households can participate in socialized division of labor, such as agricultural production trusteeship and production service outsourcing, thus lowering the threshold for participation in low-carbon operations (Ran et al., 2023). Therefore, future research should focus on the role and co-occurrence of small farming households in the development of low-carbon agriculture.

6.3 Strengthening international cooperation in agricultural science and technology

The severe climate change and the sudden outbreak of COVID-19 have had a significant impact on the global economy, leading countries to recognize the importance of open cooperation and collective participation in addressing global crises. Strengthening international cooperation in agricultural technology not only helps leverage the comparative advantages of agricultural science and technology across countries while enhancing innovation capacity, it also improves the core competitiveness of the agricultural industry and reduces the technological gap between agricultural powers. Currently, international cooperation between agricultural research institutions faces critical issues such as funding shortages, the need for optimized collaboration models, and the need for talent development (Yu and Du, 2021). In terms of funding, it is necessary to strengthen international exchanges and cooperation, improve financial subsidy policies for international agricultural cooperation, and support the smooth "going global" of agricultural science and technology (Guan and Hu, 2019). In terms of collaboration models, focusing on agricultural technology cooperation, establishing national modern agricultural demonstration zones, and gradually developing agriculture-industry chain collaboration can effectively utilize agricultural resources and fully exploit the value of land and labor productivity (Cabral et al., 2023). Regarding talent development, constructing a sound talent training system, establishing a normalized mechanism for scientific and technological exchanges, and conducting diversified activities such as scientific and technological education, popular science promotion and research conferences can effectively promote the cultivation and construction of agricultural science and technology talents (Yao and Wu, 2022).

7 Discussion

This study is based on an analysis of Chinese agricultural science and technology research from the perspective of a low-carbon economy using the Citespace visualization analysis method. A total of 3,315 CSSCI journal articles from the CNKI database and 1,627 SSCI journal articles from the WOS database were analyzed. The study compared Chinese and international research in this field and provided an outlook regarding future research trends. The research findings indicate that Chinese agricultural science and technology research is characterized by a focus on agricultural technology as its foundation and is guided by sustainable development principles in order to construct a modern agricultural production system. The evolution of this research can be divided into stages including traditional agricultural, modern agricultural, and high-quality agricultural development respectively. While there are similarities between Chinese and international agricultural science and technology research, differences exist in terms of the study of low-carbon agriculture, perspectives on agricultural science and technology research, and the agricultural technology system.

Previous studies on Chinese agricultural science and technology research have primarily focused on analyzing research hotspots and evolutionary trends based on CNKI sources (Lai et al., 2019; Wang Y. et al., 2022), overlooking the progress of international research achievements and without developing a comprehensive perspective. Chen Q. et al. (2016) examined research articles related to agricultural science and technology innovation from the WOS database, analyzing the differences between domestic and international agricultural science and technology innovation to a certain extent. However, due to the limitations of a single database, their research need to be extended. Both domestic and international literature research has yielded abundant results and developed innovative knowledge structures and frontiers. Therefore, this study combines the CNKI and WOS databases to analyze the research dynamics and evolutionary trends of Chinese agricultural science and technology research from the perspective of the low-carbon economy. It also provides a more comprehensive analysis of the differences between domestic and international agricultural science and technology research, offering a significant reference value for other agricultural countries to develop agricultural science and technology to support a low-carbon economy.

This study found that the overall scale of research publications in China is much larger than that of international publications, which is consistent with Chen's (2019) study while reflecting the high level of attention paid by the Chinese academic community to the theme of low-carbon agriculture. However, the study also reveals that the volume of internationally relevant literature in the CNKI database is relatively small, indicating a need to strengthen the exchange of agricultural science and technology research between China and other countries. In addition, the study identifies the stage-specific characteristics of Chinese agricultural science and technology research, with different stages focusing on different targets such as the early promotion of agricultural productivity, mid-term emphasis on developing green modern agriculture, and the current stage which aims to support the low-carbon transformation of agriculture. Furthermore, the study provides a comprehensive and systematic review of measurement methods for agricultural carbon emissions, carbon sinks, and carbon emission efficiency, as well as identifying the influencing factors of carbon emissions and relevant theories of low-carbon agriculture, thereby deepening the exploration of the essence of low-carbon agriculture.

There are some limitations to this study. Firstly, due to the majority of selected literature on low-carbon agriculture being concentrated in the field of economics, there needs to be more interdisciplinary coverage of politics, ecology, and other fields, resulting in certain biases in the research content. Secondly, the study remains at a theoretical level of analysis and requires more specific interpretations at the practical level. Future research should concentrate on empirical studies on agricultural science and technology research. Lastly, the Citespace software has limitations in terms of the intelligent identification of keywords and subject terms, requiring manual analysis and merging by researchers, which may affect the accuracy of the results generated. To enhance the reliability and comprehensiveness of agricultural science and technology research, it is necessary to expand the sample size of the literature and introduce a multiplicity of analysis methods.

8 Conclusion and implications

This research utilizes data from the CNKI and WOS core databases, combining bibliometrics and information visualization methods, to summarize and analyze the distribution and structural relationship of research hotspots in agricultural technology from the perspective of a low-carbon economy between 1998 and 2023. It also compares Chinese and international research and offers an outlook on future research trends. The results indicate the following: 1) the overall quantity of agricultural technology research in China experienced an initial increase followed by a decline, with related research gradually maturing. Highly cited journals mainly originate from the fields of agricultural economics and scientific research management. The critical research topics focus on agricultural technology, industrialization, modern agriculture, and low-carbon agriculture, thus highlighting the characteristics of building a modern agricultural production system based on agricultural technology, one guided by the concept of sustainable development; 2) from the perspective of supporting a low-carbon economy with agricultural technology, relevant research can be divided into three major areas based on theoretical foundations and factors influencing carbon emissions. These areas include: the economy as the core factor leading to the high-speed growth of carbon emissions in traditional agricultural production, institutions as an essential means to address agricultural carbon emissions, and technology as the key to accelerating the transformation to low-carbon agriculture; 3) the development trajectory of agricultural technology research in China can be divided into three stages: the stage of traditional agricultural development from 1998 to 2003, which led to severe ecological damage while addressing food security through technological advancements; the stage of modern agricultural development from 2004 to 2010, which focused on the modernization of characteristic Chinese forms of agriculture; and the stage of high-quality agricultural development from 2011 to 2023, which relied on digital empowerment to build an efficient, low-energy consumption, and low-carbon emission agricultural development model; 4) the evolution trajectory of agricultural technology research in China is similar to that of international research, but there are differences in terms of the research on the connotations of low-carbon agriculture, agricultural technology research perspectives, and agricultural technology system research respectively.

Based on these findings, we propose the following policy recommendations to promote the development of low-carbon agriculture in China: 1) increase investment in agricultural technology. China needs to increase investment in agricultural technology and mobilize private investment through market mechanisms by encouraging enterprises, farmers, and the general public to participate actively in agricultural emission reduction efforts; 2) optimizing agricultural subsidy policies. China should adopt appropriate policy tools for different agricultural production entities by significantly increasing green subsidies for small farmers based on actual needs. This will incentivize small farmers to enthusiastically meet their carbon reduction responsibilities; 3) strengthen international cooperation in agricultural technology. China needs to deepen scientific and technological cooperation in the field of low-carbon agriculture with countries participating in the "Belt and Road" initative. By leveraging the comparative advantages of agricultural technology in different countries, China can enhance its innovation capacity in agricultural technology, improve the core competitiveness of its agricultural industry, and reduce the technological gap between China and other agricultural powerhouses.

Author contributions

WJ: Funding acquisition, Investigation, Project administration, Supervision, Writing–original draft, Writing–review and editing, Conceptualization. SW: Data curation, Formal analysis, Software, Visualization, Writing–original draft. YZ: Conceptualization, Writing–review and editing, Formal analysis, Investigation, Supervision. GZ: Project administration, Resources, Supervision, Writing–review and editing, Methodology. LX: Software, Validation, Writing–review and editing, Formal analysis. YX: Investigation, Supervision, writing–review and editing, Resources.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This paper was supported by the Humanities and Social Science Project of Ministry of Education of China (18YJC790066), Shandong Major R&D project (Soft Science) (2023RKY04010), Shandong Natural Science Foundation Youth Project (ZR2023QG037), Qingdao Science and Technology Innovation Strategy Research Project (QUT-SK-2023-ZX-0015).

Acknowledgments

The authors thank the editor and the reviewers for providing constructive suggestions and comments on the manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Abah, J. O., Ishaq, M., and Wada, A. C. (2010). The role of biotechnology in ensuring food security and sustainable agriculture. *Afr. J. Biotechnol.* 9, 8896–8900. doi:10.5897/AJB2010.000-3319

Ahmed, A. A., Nazzal, M. A., and Darras, B. M. (2021). Cyber-physical systems as an enabler of circular economy to achieve sustainable development goals: a comprehensive review. *Int. J. Precis. Eng. Manuf-GT.* 9, 955–975. doi:10.1007/s40684-021-00398-5

Ambali, O. I., Areal, F. J., and Georgantzís, N. (2021). Improved rice technology adoption: the role of spatially-dependent risk preference. *Agric* 11, 691. doi:10.3390/agriculture11080691

Bamière, L., Bellassen, V., Angers, D. A., Cardinael, R., Ceschia, E., Chenu, C., et al. (2022). A marginal abatement cost curve for climate change mitigation by additional carbon storage in French agricultural land. *J. Clean. Prod.* 383, 135423. doi:10.1016/j.jclepro.2022.135423

Bederson, B. B., and Shneiderman, B. (2004). *The craft of information visualization: readings and reflections*, 51. Morgan Kaufmann Pub, 139. doi:10.1016/B978-155860915-0/50044-5

Cabral, F. D., Yin, C., Wague, J. L., and Yin, Y. (2023). Analysis of China–Angola agricultural cooperation and strategies based on SWOT framework. *Sustain* 15 (10), 8378. doi:10.3390/su15108378

Che, S. (2022). Can "energy saving and low carbon" policy realize win-win of enterprises' production performance? *Fin. Econ.* 9, 91–106. (in Chinese).

Chen, C. (2006). CiteSpace II: detecting and visualizing emerging trends and transient patterns in scientific literature. *J. Assoc. Inf. Sci. Technol.* 57, 359–377. doi:10.1002/asi.20317

Chen, Q., Zhang, J., and Yu, H. (2016). A study on research hot-spots and frontiers of agricultural science and technology innovation – visualization analysis based on the Citespace III. *Ag. Econ. Zem. Ek.* 62, 429–445. doi:10.17221/207/2015-AGRICECON

Chen, Y., Han, B., and Liu, W. (2016). Green technology innovation and energy intensity in China. *Nat. Hazards.* 84, 317–332. doi:10.1007/s11069-016-2158-7

Chen, Y., Li, M., Su, K., and Li, X. (2019). Spatial-Temporal characteristics of the driving factors of agricultural carbon emissions: empirical evidence from Fujian, China. *Energies* 12 (16), 3102. doi:10.3390/en12163102

Cheng, M., and Yao, W. (2022). Trend prediction of carbon peak in China's animal husbandry based on the empirical analysis of 31 provinces in China. *Environ. Dev. Sustain.* 2022, 1–18. doi:10.1007/s10668-022-02794-6

Cheng, P., Tang, H., Lin, F., and Kong, X. (2023). Bibliometrics of the nexus between food security and carbon emissions: hotspots and trends. *Environ. Sci. Pollut. Res.* 30 (10), 25981–25998. doi:10.1007/s11356-022-23970-1

Cui, Q., Yang, J., and Dong, W. (2014). Determinants of the variance of estimations on China's carbon emission: based on meta-analysis. *En. Proc.* 61, 1150–1162. doi:10.1016/j.egypro.2014.11.1043

Dai, X., Sun, Z., and Müller, D. (2021). Driving factors of direct greenhouse gas emissions from China's pig industry from 1976 to 2016. *J. Integr. Agric.* 20 (1), 319–329. doi:10.1016/S2095-3119(20)63425-6

Dong, M. T. (2016). Research on the correlation between agricultural carbon emissions and industrial structure in China. *J. Arid. Land Res. Environ.* 30 (10), 7–12. (in Chinese). doi:10.13448/j.cnki.jalre.2016.309

FAO (2022). *World food and agriculture-statistical Yearbook 2022*. Rome. doi:10.4060/cc2211en

Glänzel, W. (2015). Bibliometrics-aided retrieval: where information retrieval meets scientometrics. *Scientometrics* 102, 2215–2222. doi:10.1007/s11192-014-1480-7

Gu, G., Wang, Z., and Wu, L. (2020). Carbon emission reductions under global low-carbon technology transfer and its policy mix with R&D improvement. *Energy* 216 (11), 119300. doi:10.1016/j.energy.2020.119300

Guan, X., and Hu, Z. (2019). Foreign cooperation in agriculture of China agriculture scientific research institutes under the "one belt and one road" initiative. *Sci. Manage. Res.* 37 (5), 120–126. (in Chinese). doi:10.19445/j.cnki.15-1103/g3.2019.05.020

Guo, M., Jia, X., Huang, J., Kumar, K., and Burger, N. (2015). Farmer field school and farmer knowledge acquisition in rice production: experimental evaluation in China. *Agric. Ecosyst. Environ.* 209, 100–107. doi:10.1016/j.agee.2015.02.011

Huang, W., Wu, F., Han, W., Li, Q., Han, Y., Wang, G., et al. (2022). Carbon footprint of cotton production in China: composition, spatiotemporal changes and driving factors. *Sci. Total Environ.* 821, 153407. doi:10.1016/j.scitotenv.2022.153407

Huang, X. H., and Nie, F. Y. (2023). Mechanism research on digitalization driving green and low-carbon transformation of farmers' agriculture. *J. Northwest A&F Univ.* 23 (1), 30–37. (in Chinese). doi:10.13968/j.cnki.1009-9107.2023.01.04

Huang, X., Yang, F., and Fahad, S. (2022). The impact of digital technology use on farmers' low-carbon production behavior under the background of carbon emission peak and carbon neutrality goals. *Front. Environ. Sci.* 10, 1002181. doi:10.3389/fenvs.2022.1002181

Jiang, C. (2011). The proof of development model of agricultural productive service industry: viewing from anhui province. *Reform* 1, 74–82. (in Chinese).

Jiang, S., and Jiang, F. (2023). Research on the impact of science and technology finance policy on urban carbon emission performance – a quasi-natural experiment based on "the pilot policy of combining science and technology with finance". *Soft Sci.* 10 (3), 1–12. (in Chinese).

Jiang, T., Li, S., Yu, Y., and Peng, Y. (2022). Energy-related carbon emissions and structural emissions reduction of China's construction industry: the perspective of input–output analysis. *Environ. Sci. Pollut. Res.* 29, 39515–39527. doi:10.1007/s11356-021-17604-1

Knudsen, M. T., Meyer-Aurich, A., Olesen, J. E., Chirinda, N., and Hermansen, J. E. (2014). Carbon footprints of crops from organic and conventional arable crop rotations – using a life cycle assessment approach. *J. Clean. Prod.* 64, 609–618. doi:10.1016/j.jclepro.2013.07.009

Lai, X., Zhang, J., and Zhang, Z. (2019). Analysis of the research trend of agricultural technology in China based on CSSCI literature from 1998 to 2017. *Stud. Sci. Manag.* 37, 128–134. (in Chinese). doi:10.19445/j.cnki.15-1103/g3.2019.03.025

Li, D., Fan, K., Lu, J., Wu, S., and Xie, X. (2022). Research on spatio-temporal pattern evolution and the coupling coordination relationship of land-use benefit from a low-carbon perspective: a case study of fujian province. *Land* 11 (9), 1498. doi:10.3390/land11091498

Li, D., and Li, C. (2020). A 10-year review of strategic emerging industries: hotspots, trends, and frontiers. *Sci. Manag. Res.* 38 (04), 48–54. (in Chinese). doi:10.19445/j.cnki.15-1103/g3.2020.04.008

Li, H., Mao, S., Zhai, B., Chen, Y., Li, G., Zhang, Y., et al. (2021). LncRNAs and their regulatory networks in breast muscle tissue of Chinese Gushi chickens during late postnatal development. *Sci. Technol. Manage. Res.* 41 (22), 44–52. (in Chinese). doi:10.1186/s12864-020-07356-6

Li, J. (2010). Dynamics and path selection of the "promoting agriculture through industry" mechanism from the perspective of agricultural industry chain. *Issues Agric. Econ.* 31 (3), 24–30+110. (in Chinese). doi:10.13246/j.cnki.iae.2010.03.011

Li, J., Li, S., Liu, Q., and Ding, J. (2022). Agricultural carbon emission efficiency evaluation and influencing factors in Zhejiang Province, China. *Front. Environ. Sci.* 10, 1005251. doi:10.3389/fenvs.2022.1005251

Li, S., Sheng, M., Yuan, F., and Yin, J. (2021). Effect of land cover change on total SOC and soil PhytOC accumulation in the karst subtropical forest ecosystem, SW China. *J. Soils Sediments* 21 (7), 2566–2577. doi:10.1007/s11368-021-02970-7

Li, W., and Sun, B. (2014). Knowledge structure and research hotspots in western economic geography: a quantitative study based on CiteSpace. *Econ. Geogr.* 34 (4), 7–12+45. (in Chinese). doi:10.15957/j.cnki.jjdl.2014.04.003

Li, X., and Huo, X. (2008). Current situation and development strategy of seed industry in China. *J. Northwest A&F Univ.* 3, 62–66. (in Chinese). doi:10.3969/j.issn.1671-895X.2008.02.002

Liao, Y., Zhang, B., Kong, X., Wen, L., Yao, D., Dang, Y., et al. (2022). A cooperative-dominated model of conservation tillage to mitigate soil degradation on cultivated land and its effectiveness evaluation. *Land* 11 (8), 1223. doi:10.3390/land11081223

Liu, J., Yu, C., Sun, Y., Baek, C., Han, X. H., Athiraman, U., et al. (2012). Noxious stimulation attenuates ketamine-induced neuroapoptosis in the developing rat brain. *Econ. Rev. J.* 6, 64–71. (in Chinese). doi:10.1097/ALN.0b013e31825ae693

Liu, L., Zhu, Y., and Guo, S. (2020). The evolutionary game analysis of multiple stakeholders in the low-carbon agricultural innovation diffusion. *Complex* 2020, 1–12. doi:10.1155/2020/6309545

Lu, Y., Tian, Y., and Zhou, L. (2023). Spatial-temporal evolution and influencing factors of agricultural carbon emissions in Sichuan Province. *Chin. J. Agric. Resour. Reg. Plan.* 44 (1), 1–14. (in Chinese). doi:10.21203/rs.3.rs-2564480/v1

Luo, J., Hu, M., Huang, M., and Bai, Y. (2022). How does innovation consortium promote low-carbon agricultural technology innovation: an evolutionary game analysis. *J. Clean. Prod.* 384 (5), 135564. doi:10.1016/j.jclepro.2022.135564

Magrini, E., and Vigani, M. (2016). Technology adoption and the multiple dimensions of food security: the case of maize in Tanzania. *Food* 8, 707–726. doi:10.1007/s12571-016-0593-7

Pang, J., Li, H., Lu, C., Lu, C., and Chen, X. (2020). Regional differences and dynamic evolution of carbon emission intensity of agriculture production in China. *Int. J. Environ. Res. Public Health.* 17 (20), 7541. doi:10.3390/ijerph17207541

Piwowar, A. (2019). Low carbon agriculture in Poland – theoretical and practical challenges. *Pol. J. Environ. Stud.* 28 (4), 2785–2792. doi:10.15244/PJOES/92211

Ran, G., Wang, G., Du, H., and Lv, M. (2023). Relationship of cooperative management and green and low-carbon transition of agriculture and its impacts: a case study of the western tarim river basin. *Sustain* 15 (11), 8900. doi:10.3390/su15118900

Samoraj, M., Mironiuk, M., Witek-Krowiak, A., Izydorczyk, G., Skrzypczak, D., Mikula, K., et al. (2022). Biochar in environmental friendly fertilizers - prospects of development products and technologies. *Chemosphere* 296, 133975. doi:10.1016/j.chemosphere.2022.133975

Scharlemann, J. P., Brock, R. C., Balfour, N., Brown, C., Burgess, N. D., Guth, M. K., et al. (2020). Towards understanding interactions between Sustainable Development

Goals: the role of environment-human linkages. *Sustain. Sci.* 15, 1573–1584. doi:10.1007/s11625-020-00799-6

Schewe, R. L., and Stuart, D. (2015). Diversity in agricultural technology adoption: how are automatic milking systems used and to what end? *Agric. Hum. Values.* 32 (2), 199–213. doi:10.1007/s10460-014-9542-2

Shan, T., Xia, Y., Hu, C., Zhang, S., Zhang, J., Xiao, Y., et al. (2022). Analysis of regional agricultural carbon emission efficiency and influencing factors: case study of Hubei Province in China. *PLoS ONE* 17 (4), e0266172. doi:10.1371/journal.pone.0266172

Sinyolo, S. (2020). Technology adoption and household food security among rural households in South Africa: the role of improved maize varieties. Technol. *Soc.* 60, 101214. doi:10.1016/j.techsoc.2019.101214

Spanaki, K., Karafili, E., Sivarajah, U., Despoudi, S., and Irani, Z. (2021). Artificial intelligence and food security: swarm intelligence of agri tech drones for smart agri food operations. *Prod. Plan. Control.* 33, 1498–1516. doi:10.1080/09537287.2021.1882688

Sun, D., and Cheng, S. (2021). The realistic dilemma and policy recommendations of agricultural technology innovation system promoting the development of low-carbon agriculture. *Sci. Manage. Res.* 39 (4), 125–130. (in Chinese). doi:10.19445/j.cnki.15—1103/g3.2021.04.019

Tian, H. W. (2023). Analysis on the digital economy's empowerment of green and low-carbon development under the "Dual Carbon" goal. *Zhongzhou Acad. J.* 9, 30–39. (in Chinese). doi:10.3969/j.issn.1003-0751.2023.09.005

Tian, Y., and Yin, M. (2022). Recalculating China's agricultural carbon emissions: basic status, dynamic evolution, and spatial spillover effects. *Chin. Rural. Econ.* 2022 (03), 104–127. (in Chinese).

Wang, J., Chen, Q., and Gu, J. (2022). Hotspots and evolutionary trends of agricultural technology innovation in China: a visualization analysis based on CiteSpace. *Stud. Sci. Manage.* 42, 8–16. (in Chinese). doi:10.3390/life13010008

Wang, J., and Xiao, H. (2007). Analysis of the effect of China's seed subsidy, agricultural machinery subsidy and agricultural tax reduction and exemption policy. *Issues Agric. Econ.* 2007 (2), 24–28. (in Chinese). doi:10.3969/j.issn.1000-6389.2007.02.004

Wang, X., Fu, M., Ren, J., and Qu, X. (2007). Evaluation of different culture conditions for high-level soluble expression of human cyclin A2 with pET vector in BL21 (DE3) and spectroscopic characterization of its inclusion body structure. *Econ. Rev.* 5, 27–34. doi:10.1016/j.pep.2007.05.011

Wang, Y. (2008). On low-carbon agriculturaleconomy. *Chin. Agric. Inf.* 8, 12–15. (in Chinese). doi:10.3969/j.issn.1672-0423.2008.08.005

Wang, Y., Tao, F., Yin, L., and Chen, Y. (2022). Spatiotemporal changes in greenhouse gas emissions and soil organic carbon sequestration for major cropping systems across China and their drivers over the past two decades. *Sci. Total Environ.* 833 (7), 155087. doi:10.1016/j.scitotenv.2022.155087

Warchold, A., Pradhan, P., and Kropp, J. P. (2020). Variations in sustainable development goal interactions: population, regional, and income disaggregation. *Sustain. Dev.* 29 (2), 285–299. doi:10.1002/sd.2145

Weng, B., Wang, Y., and Lei, J. (2009). On the development of circular economy and the construction of low-carbon agriculture. *J. Poyang Lake* 3, 92–102. (in Chinese).

Winkler, K., Yang, H., Ganzenmüller, R., Fuchs, R., Ceccherini, G., Duveiller, G., et al. (2023). Changes in land use and management led to a decline in Eastern Europe's terrestrial carbon sink. *Commun. Earth Environ.* 4 (1), 237. doi:10.1038/s43247-023-00893-4

Xi, X. (2007). Preliminary study on industrial integration and multifunctional agriculture construction in China. *Fujian Trib.* 9, 20–23. (in Chinese). doi:10.3969/j.issn.1671-8402.2007.09.005

Xiang, C., Jia, X., Huang, J., Hu, R., Zhang, F., Cui, Z., et al. (2012). The impact of agricultural technology training on Farmers' nitrogen fertilizer application behavior: an empirical study based on maize production in Shouguang City, Shandong Province. *J. Agric. Tech. Econ.* 209 (9), 4–10. (in Chinese). doi:10.13246/j.cnki.jae.2012.09.001

Xiao, P., Zhang, Y., Qian, P., Lu, M., Yu, Z., Xu, J., et al. (2022). Spatiotemporal characteristics, decoupling effect and driving factors of carbon emission from cultivated land utilization in Hubei Province. *Int. J. Environ. Res. Public Health* 19 (15), 9326. doi:10.3390/ijerph19159326

Xiao, X., Liu, C., Liu, Z., Tan, H., Li, S., Zhang, Y., et al. (2022). Characteristics, driving factors and trend prediction of agriculture carbon emission in the Three Gorges Reservoir Area (Hubei Section). *Chin. J. Agric. Resour. Reg. Plan.* 37 (1), 1–14. (in Chinese).

Yang, H., Zhu, Q., and Liang, Y. (2011). Unified subject and multiple subject: the contingency construction of agricultural socialized service system organization. *J. Chongqing Univ.* 17 (2), 51–56. (in Chinese). doi:10.3969/j.issn.1008-5831.2011.02.009

Yang, Y., Lin, W., and Zhang, L. (2017). Agricultural technological progress, technical efficiency, and grain production: an empirical analysis based on provincial panel data in China. *J. Agric. Tech. Econ.* 265 (5), 46–56. (in Chinese). doi:10.13246/j.cnki.jae.2017.05.005

Yang, Y., Sun, K., Han, L., Chen, Y., Liu, J., and Xing, B. (2022). Biochar stability and impact on soil organic carbon mineralization depend on biochar processing, aging and soil clay content. *Soil Biol. biochem.* 169, 108657. doi:10.1016/j.soilbio.2022.108657

Yang, Z. (2004). The theory and practice of optimizing agricultural industrial structure-a case study of Jingmen City, Hubei Province. *J. Agric. Econ.* 3, 65–67. (in Chinese). doi:10.3969/j.issn.1000-6389.2004.03.016

Yao, S., and Wu, G. (2022). Research on the efficiency of green agricultural science and technology innovation resource allocation based on a three-stage DEA model—a case study of anhui province, China. *Int. J. Environ. Res. Public Health.* 19 (20), 13683. doi:10.3390/ijerph192013683

Yu, J., and Du, L. (2021). Normal mechanism for high-quality agricultural science and technology cooperation between China and countries along the belt and road. *Sci. Technol. Manage. Res.* 41 (20), 17–23. (in Chinese). doi:10.3969/j.issn.1000-7695.2021.20.003

Yu, Y., Jiang, T., Li, S., Li, X., and Gao, D. (2020). Energy-related CO2 emissions and structural emissions' reduction in China's agriculture: an input-output perspective. *J. Clean. Prod.* 276, 124169. doi:10.1016/j.jclepro.2020.124169

Yu, Z., Jiang, S., Cheshmehzangi, A., Liu, Y., and Deng, X. (2023). Agricultural restructuring for reducing carbon emissions from residents' dietary consumption in China. *J. Clean. Prod.* 387, 135948. doi:10.1016/j.jclepro.2023.135948

Yuzhen, S. (2021). Research on smart agricultural waste discharge supervision and prevention based on big data technology. *Acta Agric. Scand. Sect. B Soil Plant Sci.* 71, 683–695. doi:10.1080/09064710.2021.1939409

Zapata-Cantú, L., and Gonzalez, F. R. (2021). Challenges for innovation and sustainable development in Latin america: the significance of institutions and human capital. *Sustain* 13 (7), 4077. doi:10.3390/su13074077

Zeleke, B. D., Geleto, A. K., Asefa, S., and Komicha, H. H. (2022). Adoption and impact of improved wheat varieties on productivity and welfare among smallholder farmers in the Arsi Highland of Ethiopia. *Agrekon* 61, 207–228. doi:10.1080/03031853.2022.2044359

Zhang, H. (2020). Development of modern agriculture in the context of rural revitalization. *Quest* 317 (1), 124–131. (in Chinese). doi:10.16059/j.cnki.cn43-1008/c.2020.01.036

Zhang, J., and He, K. (2022). Current situation, misunderstandings and prospects of agricultural low-carbon development under the targets of carbon peak and carbon neutrality. *J. Agric. Econ.* 9, 35–46. (in Chinese). doi:10.13246/j.cnki.iae.20220914.001

Zhang, J., Jiang, L., Guo, L., and Shen, J. (2019). Prohibitin 1 interacts with signal transducer and activator of transcription 3 in T-helper 17 cells. *Proc. 6th Int. Conf. Manage. Sci. Manage. Innov.* 219, 8–14. doi:10.1016/j.imlet.2019.12.008

Zhang, L., and Nian, F. (2004). Agricultural development and water resource changes in the Bositeng Lake basin. *Arid. Zone Res. Environ.* 36–40. (in Chinese).

Zhang, X., Zhou, X., and Liao, K. (2023). Regional differences and dynamic evolution of China's agricultural carbon emission efficiency. *Int. J. Environ. Sci. Technol.* 20 (4), 4307–4324. doi:10.1007/s13762-022-04196-7

Zhang, Y., Xu, Y., Kong, H., and Zhou, G. (2022). Spatial-temporal evolution of coupling coordination between green transformation and the quality of economic development. *Sustain* 14 (23), 16267. doi:10.3390/su142316267

Zhao, D., and Zhou, H. (2021). Livelihoods, technological constraints, and low-carbon agricultural technology preferences of farmers: analytical frameworks of technology adoption and farmer livelihoods. *Int. J. Environ. Res. Public Health.* 18 (24), 13364. doi:10.3390/ijerph182413364

Zhao, R. Y., and Xu, L. M. (2010). A knowledge graph analysis of the development and research frontiers of bibliometrics in China. *J. Libr. Sci. China.* 36 (5), 60–68. (in Chinese). doi:10.13530/j.cnki.jlis.2010.05.006

Zhao, Y., Jiao, Y., and Gao, Q. (2013). Research on the benefit mechanism of agricultural technology outsourcing service. *J. Agrotech. Econ.* 5, 28–35. (in Chinese). doi:10.13246/j.cnki.jae.2013.05.003

Zhou, N., Mao, S., and Ma, H. (2021). The realistic characteristics of Korean agricultural science and technology innovation system and its enlightenment. *World Agric.* 7, 58–68. doi:10.13856/j.cn11-1097/s.2021.07.006

Zhou, S., and Li, X. (2021). Farmer characteristics, external environment, and scientific fertilization. *J. South China Agric. Univ.* 20 (1), 50–58. (in Chinese). doi:10.7671/j.issn.1672-0202.2021.01.005

Zhu, S., and Dong, C. (2013). Dynamic deviation share analysis of agricultural structure and competitiveness in Shandong Province. *Shandong Soc. Sci.* 215 (7), 174–177. (in Chinese). doi:10.14112/j.cnki.37-1053/c.2013.07.035

Zhu, Y., and Huo, C. (2022). The impact of agricultural production efficiency on agricultural carbon emissions in China. *Energies* 15 (12), 4464. doi:10.3390/en15124464

Zhu, Y., Zhang, Y., and Piao, H. (2021). Does agricultural mechanization improve agricultural environment efficiency? Evidence from China's planting industry. *Environ. Sci. Pollut. Res.* 29, 53673–53690. doi:10.1007/s11356-022-19642-9

Zhuang, Q., Shao, Z., Kong, L., Huang, X., Li, Y., Yan, Y., et al. (2023). Assessing the effects of agricultural management practices and land-use changes on soil organic carbon stocks. *Soil Tillage Res.* 231, 105716. doi:10.1016/j.still.2023.105716

Zu, Y. (2007). Research on the optimization of agricultural industrial structure in sustainable development-taking the adjustment of agricultural industrial structure in Zhangye City, Gansu Province as an example. *Prod. Res.* 5, 25–27. (in Chinese). doi:10.19374/j.cnki.14-1145/f.2007.05.012