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Review on ecological co-culture from sustainable agriculture perspective: hotspots, evolution and frontiers

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Combining the principles of systemicity, cyclicity, and diversity in agroecosystem theory, we constructed an analytical framework for the ecological co-culture model (rice-fish + livestock + fruit mix), and attempted to reveal its synergistic mechanism and evolutionary pathway in low-carbon agriculture by bibliometric methods. The COVID-19 pandemic, which emerged in 2019, has significantly impacted agricultural production and food security, emphasizing the urgent need for high-quality, sustainable agricultural development. Although agriculture is not the largest contributor to energy use or carbon emissions, its sustainable development can reduce global energy dependency, accelerate the energy transition, and contribute to achieving carbon neutrality. Moreover, a green, low-carbon energy structure is crucial for supporting sustainable agricultural practices. This study systematically reviews current research on ecological co-culture models in low-carbon agriculture in China, offering theoretical foundations for future research and strategic insights for promoting sustainable agricultural development. Using the China National Knowledge Infrastructure (CNKI) and Web of Science (WOS) Core Collection for data retrieval and employing CiteSpace software for bibliometric analysis, the study reveals the following key findings: (1) Research is highly concentrated, with approximately 52% of studies focused on the "rice-fish symbiosis" model, while research on the "fruit trees + poultry ecological co-culture" model remains relatively sparse. Although approximately one-third of the literature addresses "low-carbon agriculture," only 2% of the articles explore the relationship between "ecological co-culture" and "low-carbon agriculture," with approximately 8% covering "vertical cultivation." (2) Both domestic and international publications primarily focus on ecology, life sciences, agriculture, and aquaculture, with minimal representation in geographical journals. (3) The CiteSpace analysis of research publications between 2008 and 2023 found that China Agricultural University and the Institute of Geographic Sciences and Natural Resources Research of the Chinese Academy of Sciences were in a leading position in the field of agriculture and life sciences. (4) There are 255 principal authors with 319 cooperative connections, indicating that there are extensive collaboration networks among scholars and significant potential for advancing research on low-carbon agriculture and ecological co-culture models in China. (5) The most prominent keywords from 2014 to 2023 include "rice," "rice-fish symbiosis," and "ecological symbiosis." Additional keywords such as "rural revitalization" and "low-carbon agricultural technology" have attracted considerable attention, with a peak intensity value of 4.8. These results reflect the evolving focus of research on low-carbon agriculture in the post-pandemic era. Over time, research priorities have shifted from vertical farming and paddy-field fish farming to food security under peak carbon and green finance, while international studies have increasingly emphasized on genetic diversity. Through a quantitative review of domestic and international literature, this paper addresses a critical gap in the study of low-carbon

ecological co-culture. In conclusion, our findings underscore that research on ecological co-culture models within low-carbon agriculture remains a critical area of focus both domestically and internationally. Continued exploration in this field will not only improve sustainable agriculture but also provide valuable insights for future research directions.

KEYWORDS

low-carbon agriculture, ecological co-culture, rice-fish farming, carbon neutrality, agricultural sustainability

1 Introduction

1.1 Ecological co-culture and sustainable agricultural development

Agriculture has been integral to China's civilization for thousands of years, contributing significantly to both production systems and cultural heritage (Zhang et al., 2022; Chen et al., 2023). While not the largest sector in terms of energy consumption or carbon emissions, sustainable agricultural development can reduce global energy dependency, accelerate energy transitions, and contribute to global carbon neutrality goals (Arko et al., 2023; Cui et al., 2020; Bihari et al., 2022). A green, low-carbon energy structure is also conducive to the sustainable development of agriculture (Ding, 2014). Conventional ecological systems such as the rice-fish-duck system—recognized as a valuable part of China's agricultural heritage—hold great potential in this regard (Zhang et al., 2022; Chen et al., 2023; Becker and Frei, 2005; Liang et al., 2020). This model, which has been practiced for over 1,300 years, integrates rice-fish symbiosis to promote mutualistic relationships, thus offering an efficient and sustainable method of food production (Lu and Li, 2006; Liu et al., 2015; Stankus and Halwart, 2017; Dai et al., 2022). Ecological co-culture systems also play a crucial role in biodiversity conservation (Frei and Becker, 2005; Zhang et al., 2014; Claire et al., 2015; Cao et al., 2017; Huang, 2020). The services provided by integrated agri-fishery systems can be categorized into three groups. The first category, provisioning services, involves the use of natural environmental conditions to support human survival through the interaction of rice field ecosystems and agricultural practices. The second category, ecological services, includes functions such as atmospheric regulation, environmental stewardship, water and soil conservation, and pollution reduction (Agus et al., 2006; Wu et al., 2016; Lin and Wu, 2020; Guo et al., 2020). Lastly, social services contribute to rural economic development, cultural preservation, social security, and food security, thereby fostering rural vitality (Costanza et al., 2017; Jin et al., 2023; Li et al., 2021; Frei and Becker, 2005).

1.2 Regional context of ecological co-culture model

The Shangshan Site, an early Neolithic settlement in the Qiantang River Basin, represents one of the earliest "primary village" stages of historical development in East Asia and serves as a key reference for studying the origins of rice farming. Rice cultivation initially emerged in the middle and lower reaches of the Yangtze River, gradually expanding from a localized area into a broader region characterized by shared environmental conditions and cultural connections. The Shangshan Culture provides significant evidence for this early model of rice farming. The Shangshan Site, recognized as both a globally significant agricultural heritage site and a national archeological site, is closely linked to the agricultural development of surrounding villages. Despite being in a major rice-growing region, the surrounding villages lack systematic and effective scientific management of rice and cash crop production. Consequently, rice and cash crop cultivation yields relatively low profits compared to other sources of income, leading a significant portion of the young and middle-aged workforce to seek employment elsewhere. The area's sandy soil, with its high water permeability, favors dry farming, with rice cultivated as a supplementary crop (Muhammad et al., 2019; Si et al., 2018; Tang and Zhang, 2022).

The research idea for this paper originates from studies conducted in villages surrounding Huangzhai Town Mountain Cultural Site in Pujiang County, Zhejiang Province, China. During this period, comparative research was also carried out on the rice-fish-duck co-farming model in neighboring counties and urban areas within Zhejiang Province. However, the mixed ecological development model proposed in this paper is distinguished by its foundation in a poultry-based co-culture mode approach, setting it apart from practices in other regions (Garrett et al., 2017; Hu et al., 2020; Xing et al., 2021; Cui et al., 2020; Yang et al., 2020). While it is acknowledged that further geographically-specific research may be required, it is clarified that the focus of this paper is on the specific regional context of China. At the same time, this study is also based on the key tasks and policy background of China's agriculture and sustainable development during the "14th Five-Year Plan" period, adhering to the integrated design of agricultural modernization and rural modernization, following the laws of agricultural production, focusing on regional characteristics, advancing the green development of agriculture, strengthening the construction of ecological civilization in the countryside, and accelerating the formation of a green, low-carbon production and living style, so as to take the path of resource-saving and environment-friendly sustainable development. Take the path of sustainable development that is resource-saving and environmentally friendly.

1.3 Historical background of low-carbon agriculture

The COVID-19 pandemic, beginning in 2019, significantly disrupted agricultural production and food security, highlighting the urgent need for sustainable agricultural development. Simultaneously, global climate change has prompted countries to set carbon-neutral

targets. However, the pandemic temporarily slowed progress in energy transition, as the economic downturn led many countries to rely more heavily on fossil fuels, such as coal and petroleum, for electricity generation. The increased burning of fossil fuels has exacerbated greenhouse gas emissions, intensifying the global greenhouse effect. The International Assessment of Agricultural Knowledge and Technology for Development (2008), conducted by the United Nations and the World Bank, emphasized the need to transition from environmentally harmful agricultural models—reliant on pesticides and chemical fertilizers-to more eco-friendly, biodiversity-supportive practices that safeguard both the environment as well as farmers' livelihoods. In response to this, agriculture has entered a new phase marked by organic, ecological, and efficient practices, collectively referred to as the "low-carbon agricultural economy" (Xie et al., 2023; Khabarov et al., 2020; Hu et al., 2015). During the 75th session of the United Nations General Assembly, China announced its intention to peak carbon dioxide emissions by 2030 and achieve carbon neutrality by 2060 (Shi et al., 2022). China's 2023 government work report and Zhejiang Province's rural revitalization implementation policies emphasize the development of ecological low-carbon agriculture practices and the steady promotion of carbon neutrality within the agricultural sector. In the post-pandemic era, addressing the challenges and opportunities associated with sustainable agricultural development and the energy transition has become critical. Carbon neutrality has emerged as a key focus of multidisciplinary research (Pan et al., 2022; Rao et al., 2022). While China's research on low-carbon agriculture is relatively recent, significant advancements have been made (Sun and Tian, 2014; Duan et al., 2020; Zhang et al., 2022; Chen et al., 2023; Ren et al., 2023). However, gaps remain in the comprehensive discussion and systematic categorization of ecological co-culture models in low-carbon agriculture (Costanza et al., 2017; Roel et al., 2012; Xiao et al., 2021; Yuan et al., 2009b; Frei et al., 2007). A comprehensive review of the research status and emerging trends in ecological co-culture models within low-carbon agriculture can provide valuable insights into developments across various disciplines.

1.4 Research significance of the ecological co-culture model

Bibliometric analysis has been widely employed in frontier research and current literature to examine the development of various disciplines, with CiteSpace emerging as a highly influential tool for visual analysis in this field (Chen et al., 2023; Shi et al., 2022; Guo et al., 2023; Li et al., 2023; Yang et al., 2010). CiteSpace combines information visualization technology with conventional bibliometric methods, enabling the creation of knowledge graphs that highlight research trends and dynamics. In this study, data from China National Knowledge Infrastructure (CNKI) and Web of Science (WOS) were analyzed using CiteSpace to explore the research status, hotspots, and development trends of ecological co-culture models in China's low-carbon agriculture. Through keyword clustering, keyword analysis, and periodic trend analysis, the study identifies research hotspots and developmental trajectories. The findings offer valuable insights for advancing low-carbon agriculture and support the global dissemination of China's new model of sustainable agricultural development.

The complementary symbiotic ecological co-culture model aims to enhance rice yield, improve the quality of fishery and poultry products, and account for the characteristics of various cash crops and mixed poultry farming based on local conditions. This model allows economic, social, and agricultural integration ecological benefits to achieve low-carbon and circular development goals. In this context, the evaluation system of the ecological co-culture model can serve as a comprehensive basis for land resource planning. Additionally, evaluating the ecosystem services provided by the integrated rice, fish, duck, fruit, and livestock mixed culture system offers valuable insights. This research can further establish an ecological compensation mechanism, preserving global agricultural cultural heritage, enhancing human wellbeing, improving natural ecological environments, and generating innovative solutions for the sustainable development of both human society and nature (Stone et al., 2023; Wu and Zhou, 2022; Wei et al., 2018; Yuan et al., 2009a).

This study centers on rice, grapes, and other cash crops in villages surrounding the Shangshan Site, using a case study of an integrated model that combines rice, fish, and duck farming with fruit and livestock mixed culture. It examines the driving factors and responses of cash crops such as rice in these villages, considering their potential contributions to future social and economic development. The findings also highlight how such integrated farming systems can promote the sustainable development of local agriculture, providing a model for adapting low-carbon agricultural practices to region-specific conditions and serving as an example for other areas. Additionally, the study employs quantitative bibliometric methods to explore the historical evolution of ecological co-culture practices in China and abroad, thereby enhancing understanding in this field and addressing existing research gaps.

2 Materials and methods

2.1 Data sources

This study draws on two major academic databases-the CNKI database and the WOS Core Collection—for literature retrieval. Fuzzy search keywords were used, including "ecological co-culture," "rice-fish-duck," "rice-fish symbiosis," "fruit tree + poultry ecological co-culture," "vineyard nesting poultry," "three-dimensional farming," and "low-carbon agriculture," covering publications from 2008 to 2023. In CNKI, the search yielded the following results: 28 articles on "ecological co-culture," 45 articles on "rice-fish-duck," 476 articles on "rice-fish symbiosis," 2 articles on "vineyard nesting poultry," 247 articles on "three-dimensional farming," and 809 articles on "low-carbon agriculture." Similarly, the search results from WOS Core Collection included 34 articles on "ecological co-culture," 34 articles on "rice-fish-duck," 646 articles on "rice-fish symbiosis," 1 article on "vineyard housed birds," 1 article on "stereoscopic planting and breeding," and 571 articles on "low-carbon agriculture." Literature records from CNKI were exported in Refworks format, and data from WOS were downloaded and saved as plain text files for further analysis. All retrieved data samples were processed using CiteSpace software. During data collection, it was noted that few studies are associated with certain keywords, and some Chinese literature lacked clarity in categorization. Furthermore, foreign literature on the low-carbon ecological co-culture model is scarce, with a significant portion authored by Chinese researchers abroad. Research

contributions by non-Chinese authors in this area are limited, leading to noticeable data. The study period was selected for two key reasons: First, it spans the years before and after the outbreak of the COVID-19 pandemic; second, even in the current year of 2024, the number of newly added relevant publications remains minimal, often in single digits, which does not significantly influence the results. Nonetheless, to ensure rigor, research content from 2024 will be updated as necessary.

2.2 Research method

2.2.1 Bibliometric analysis software

CiteSpace, a bibliometric analysis software, was employed to visualize and analyze the evolution and trends within large literature datasets. This software can be freely accessed through https://sourceforge.net/projects/CiteSpace/. For this study, CiteSpace 6.2.2 was used to investigate the research status, hot spots, and emerging trends in the relationship between ecological co-culture models and low-carbon agriculture in China. CiteSpace enables the analysis of citation patterns, keyword clustering, and authors and institution collaborations, helping to identify frontier research directions and significant contributing institutions. Compared to other bibliometric software, CiteSpace offers enhanced visualization capabilities, allowing for more intuitive and diverse representation of results.

2.2.2 Parameter setting

The analysis was conducted using the following settings: (1) the time segment selected for this study spans from 2008 to 2023. (2) Node types include research institutions, authors, and keywords. (3) The "Pathfinder" option was applied to eliminate redundant connections, while other settings were kept at their default configurations.

3 Results and analysis

3.1 Basic characteristics of the articles

This section primarily analyzes two fundamental aspects of the literature: the number of published articles and the primary source journals. The number of publications reflects the sustained interest in the research topic, while the primary source journals indicate the field's most relevant publications and preferred outlets for dissemination.

3.1.1 Number of publications

Between 2008 and 2023, a total of 2,894 papers, both domestic and international, were identified in academic reports on topics such as "ecological co-culture," "rice-fish and duck," "rice-fish symbiosis," "fruit tree + poultry ecological co-culture," "vineyard nesting poultry," "three-dimensional farming," and "low-carbon agriculture," using these terms as fuzzy search keywords. Notably, domestic research tends to focus on themes such as "rice-fish symbiosis," "rice-fish-duck," and "low-carbon agriculture."

Specifically, when analyzing the themes of "ecological co-culture," "rice-fish-duck," "rice-fish symbiosis," "fruit tree + poultry ecological co-culture," "vineyard nesting poultry," "three-dimensional farming," and "low-carbon agriculture," it becomes evident that from 2014 to 2023, there has been a steady increase in the number of published papers on "ecological co-culture" and "rice-fish-duck" model (Figure 1). Search related to "rice-fish symbiosis" revealed that approximately 58 articles are published annually, showing a significant growth trend. The number of publications on "low-carbon agriculture" has experienced a noticeable rise since 2010, with annual publications ranging between 100 and 300. Within the WOS Core Collection, the annual number of articles on "rice-fish symbiosis" ranged from 104 to 273 between 2008 and 2023, with an average annual output remaining consistently high. In contrast, "low-carbon agriculture" has seen a relatively limited number of publications during 2011–2023. However, in 2022, the number of articles on this theme reached a record high of 144. There are evident similarities and distinctions in domestic and international research on "vineyard nesting poultry" and "three-dimensional breeding." From 2008 to 2023, no studies on the "vineyard nesting poultry" ecological model were identified, revealing a research gap in this area. In contrast, research on "three-dimensional agriculture" has shown significantly higher engagement and output among domestic scholars compared to international researchers.

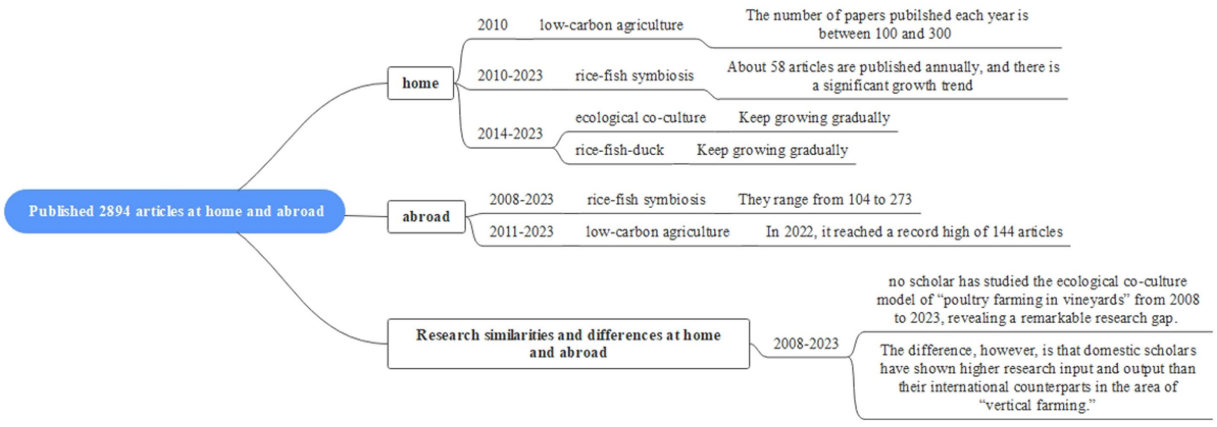

FIGURE 1
Schematic representation of the filtering process used to search and select articles based on the number of publications.

3.1.2 Primary source journal

In the study of ecological co-culture models within the context of low-carbon agriculture in China, research is predominantly concentrated in specific thematic areas. By analyzing both domestic and international journals on topics such as "ecological co-culture," "rice-fish-duck," "rice-fish," "fruit tree + poultry ecological co-culture," "vineyard nesting poultry," "three-dimensional farming," and "low-carbon agriculture," several trends and focal points emerged (Figure 2 and Table.1).

Approximately 52% of the analyzed articles focus on the "rice-fish" model, highlighting this as a major area of emphasis. In contrast, the "fruit tree + poultry ecological co-culture" model remains underrepresented in the literature. Furthermore, studies on "low-carbon agriculture" account for approximately one-third of the total articles, though few explore the direct relationship between ecological co-culture and low-carbon agriculture. In terms of specific journals, different themes are published across distinct journals. Studies on "ecological co-culture models" are frequently published in journals such as China's Agricultural Resources and Regionalization, Agriculture Ecosystems and Environment, Nature sustainability, Ecological indicators, Journal of Cleaner Production, Bioenergy research, Journal of China Agricultural University, Resources and Environment in the Yangtze River Basin, Modern Agricultural Science and Technology, Farming and Cultivation, Science and Technology Management Research, Modern Agricultural Research, Journal of Livestock Ecology, Journal of Lishui University, and Aquaculture. Research on "rice-fish-duck" systems is commonly found in journals such as Ecological journal, Journal of Applied Ecology, Journal of China Agricultural University (Social Science Edition), Sustainability, Indian journal of fisheries and Ecological indicators, Biological agriculture and horticulture, Agriculture ecosystems and environment, Chinese Agricultural History, Aquatic Science, Freshwater Fishery, Ecological Economy, Guizhou Agricultural Science, Farming and Cultivation, and Original Ecological National Culture Journal. Studies focusing specifically on the "rice-fish" system appear in publications such as Chinese journal of Eco-Agriculture, Geographical Research, Ecology Journal, Applied Ecology Journal, Agriculture ecosystems and environment, Fisheries science, Indian journal of agricultural Science, Agricultural Modernization Research, China Population, Resources and Environment, China Agricultural Science and Technology Guide, Resources Science, Journal of Environmental Science, Journal of Aquatic sciences, China Rice Science, and Regional Research and Development. Research on "vineyard nesting poultry" remains sparse, with only two Chinese articles published in Rural Bestong and Chinese Forest side products. English publications on this theme include Agriculture Ecosystems and Environment, Journal of Pest Science, Ornithological Science, Biologia, and Wilson Journal of Ornithology. The theme of "three-dimensional cultivation" is explored in journals such as Sichuan Agricultural Science and Technology, Northern Animal Husbandry, Modern agriculture, Modern Agricultural Science and Technology, China Tropical Agriculture, Friends of Fruit farmers, Practical Technology and Information of fruit trees, Genes and genomics, Remote sensing, Bioscience journal, Journal of Science field robotics, Protoplasma, Rural new technology, and Chinese livestock and poultry seed industry. Finally, studies on "low-carbon agriculture" are predominantly published in journals like Agricultural Economic Issues, Chinese Land Science, Chinese Journal of Eco-Agriculture, China Rural Observation, Agricultural Technical Economics, Economic Geography, Agricultural Resources and Regionalization in China, Agricultural Modernization Research, and Journal of Natural Resources.

3.2 Major research institutions and authors

3.2.1 Major research institutions

Using CiteSpace software to analyze research institutions from 2008 to 2023, with a one-year time slice and the node type set to "mechanism," the analysis identified 272 nodes, 421 connections, and a network density of 0.0114. The number of nodes corresponds to the research institutions

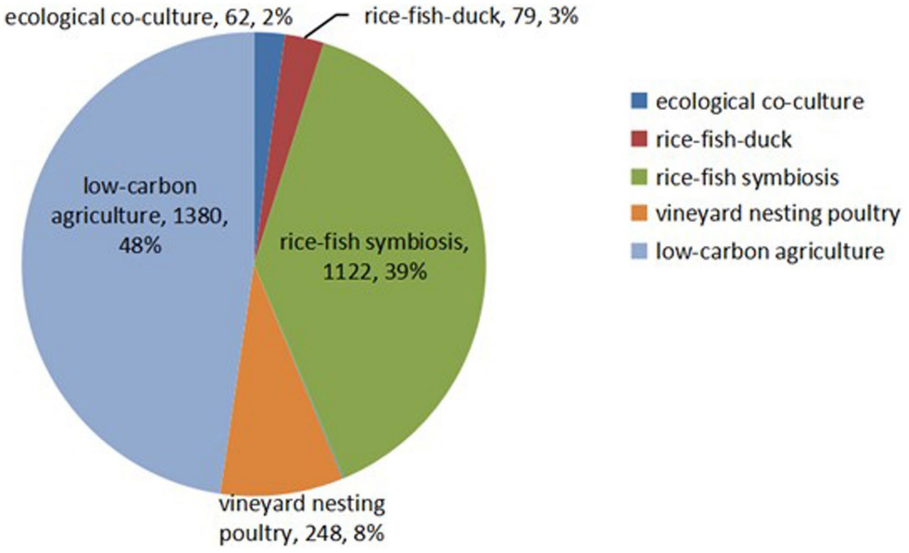

FIGURE 2
Literature review of ecological co-culture models within low-carbon agriculture in China.

TABLE 1 List of journals covering various topics related to China's low-carbon agroecological symbiosis model.

Item	Ecological co-culture	Rice-fish-duck	Rice-fish symbiosis	Fruit tree + poultry ecological co-culture	Vineyard nesting poultry	Low-carbon agriculture
1	China's Agricultural Resources and Regionalization	Ecological journal	Chinese journal of Eco-Agriculture	Sichuan Agricultural Science and Technology	Rural Bestong	Agricultural Economic Issues
2	Agriculture Ecosystems and Environment	Journal of Applied Ecology	Geographical Research	Northern Animal Husbandry	Chinese Forest side products	Chinese Land Science
3	Nature sustainability	Journal of China Agricultural University (Social Science Edition)	Ecology Journal	Modern agriculture	Agriculture Ecosystems and Environment	Chinese Journal of Eco-Agriculture
4	Ecological indicators	Sustainability	Applied Ecology Journal	Modern Agricultural Science and Technology	Journal of Pest Science	China Rural Observation
5	Journal of Cleaner Production	Indian journal of fisheries and Ecological indicators	Agriculture ecosystems and environment	China Tropical Agriculture	Ornithological Science	Agricultural Technical Economics
6	Bioenergy research	Biological agriculture and horticulture	Fisheries science	Friends of Fruit farmers	Biologia	Economic Geography
7	Journal of China Agricultural University	Agriculture ecosystems and environment	Indian journal of agricultural Science	Practical Technology and Information of fruit trees, Genes and genomics	Wilson Journal of Ornithology	Agricultural Resources and Regionalization in China
8	Resources and Environment in the Yangtze River Basin	Chinese Agricultural History	Agricultural Modernization Research	Genes and genomics		Agricultural Modernization Research
9	Modern Agricultural Research	Aquatic Science	China Population	Remote sensing		Journal of Natural Resources
10	Journal of Livestock Ecology	Freshwater Fishery	Resources and Environment	Bioscience journal		
11	Journal of Lishui University	Ecological Economy	China Agricultural Science and Technology Guide	Journal of Science field robotics		
12	Aquaculture	Guizhou Agricultural Science	Resources Science	Rural new technology		
13		Farming and Cultivation	Journal of Environmental Science	Chinese livestock and poultry seed industry		
14		Original Ecological National Culture Journal	Journal of Aquatic sciences			
15			China Rice Science			
16			Regional Research and Development			

identified in the analysis, while the connections between nodes represent instances where institutions are referenced together in the literature, indicating collaborative relationships. The network density measures the proportion of actual interconnected relationships relative to the theoretical maximum number of possible relationships in the network, although there is no established standard for interpreting this value. Figure 3 reveals certain similarities between domestic and international research institutions. Notably, key institutions such the Institute of Geographical Sciences and Natural Resources Research of the Chinese Academy of Agricultural Sciences, the Chinese Academy of Agricultural Sciences, China Agricultural University, Nanjing Agricultural University, and Zhejiang University have emerged as significant focal points. These institutions have made substantial contributions to low-carbon agriculture research, reflecting their scientific research capabilities. Moreover, the strong connections between nodes suggest robust partnerships, either within the same department or among institutions located in the same geographic region, highlighting the importance of collaborative research in this field.

3.2.2 Principal authors

In the CiteSpace analysis using the "Author" node type, the collaboration network revealed 255 authors and 319 connections,

resulting in a network density of 0.0099 (Figure 4). This indicates considerable potential for further development in the study of low-carbon agriculture and ecological co-culture models in China, with a large number of researchers and extensive collaboration. The cooperative network, illustrated in Figure 4, highlights five major research teams actively contributing to the field of low-carbon agriculture and ecological co-culture model in China:

1 Min Qingwen leads a prominent research team (indicated by circle size), closely connected with Sun Yehong and Cheng Shengkui, indicating significant collaborative efforts. Min Qingwen's team focuses on environmental impact assessments, particularly based on tourists' environmental responsibility behavior, food tourism preferences, the rice-fish symbiosis system, and traditional agricultural systems (Cui et al., 2020).
2 Chen Xin's team (indicated by the red circle area) has a close collaboration with Tang Jianjun, Hu Liangliang, Wu Minfang, Guo Liang, and Zhang Jian. Their research is concentrated on the productivity and nitrogen-use efficiency of rice-crab systems (Hu and Jing, 2021), sustainable yields in rice-fish co-cultivation (Chen et al., 2020; Xie et al., 2011), the relationship between plant diversity and yield of border crops (Wan and Yang, 2018), and rice co-cultivation with soft-shell turtles (Zhang et al., 2016; Jian et al., 2016). This team has also focused on rice-fish symbiosis systems, contributing to innovations in sustainable agriculture (Hu et al., 2015).
3 Cheng Shengkui leads another key research group (indicated by the green circle area), working closely with Zhang Dan and Liu Husheng. Their research has explored the use of carbon and nitrogen stable isotopes to study the food web structures and trophic relationships in paddy ecosystems (Zhang and Liu, 2010). This team has also assessed the ecological service function value of rice-fish symbiotic systems (Zhang and Liu, 2010), emphasizing the importance of these systems in promoting sustainable agricultural practices while preserving cultural and ecological diversity (Sun and Zuo, 2008; Ye et al., 2022).
4 Huang Huang's team (indicated by red circles), in collaboration with Chen Can's research team, has focused on ecological co-culture and the comprehensive utilization of rice fields. Their research includes analyzing the effects of rice-fish-chicken symbiosis on rice population dynamics (Ma and Huang, 2023; Yuan et al., 2022), crop yields, nitrogen and phosphorus balances, and crayfish breeding models (Tang et al., 2020). Additionally, they have investigated the effects of various paddy ecological co-culture models on double-cropping rice yields and CH_4 emissions (Chen et al., 2023), the influence of different rice-fish models on the yield and quality of recycled rice (Chen et al., 2021), and the impact of diverse paddy cultivation models on the physical and chemical properties of soil and water, as well as rice yield (Tang et al., 2020).

3.3 Research hotspot analysis

3.3.1 Keyword clustering

Keyword clustering serves as a tool to identify temporal shifts in research focal points by tracking significant increases or decreases in

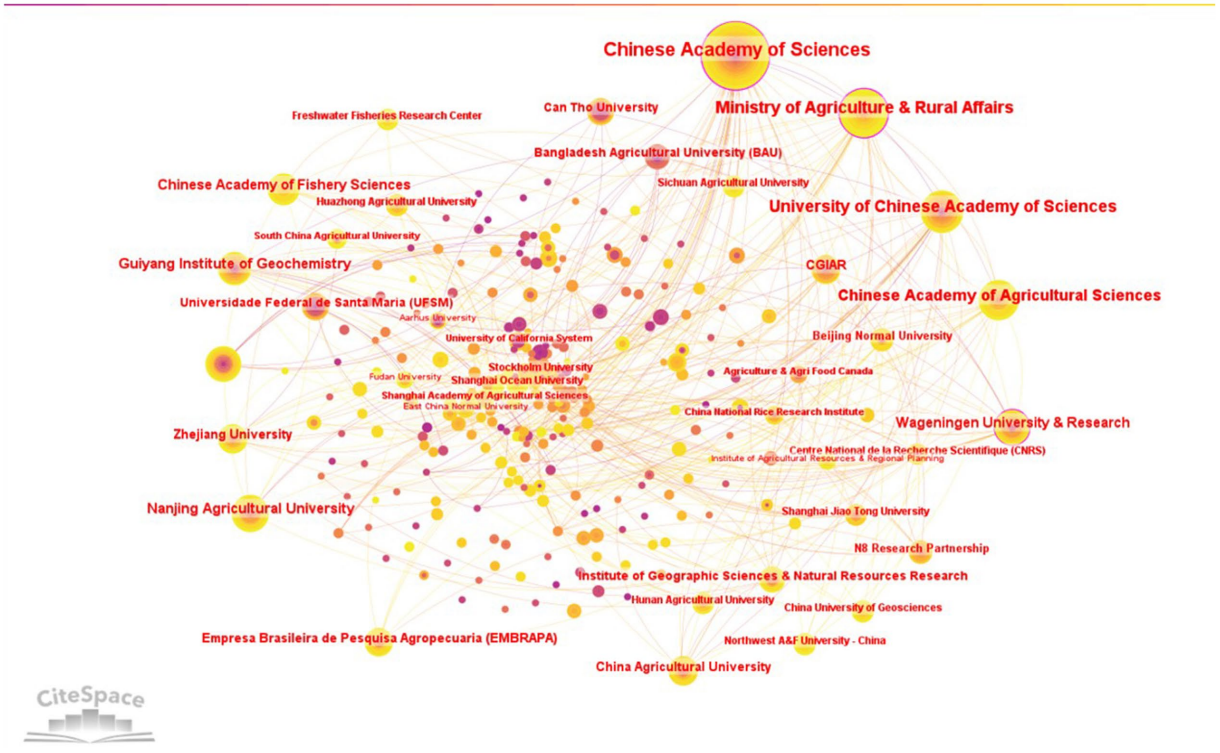

FIGURE 3
Major research institutions, both domestic and international, engaged in low-carbon agriculture and ecological co-culture models.

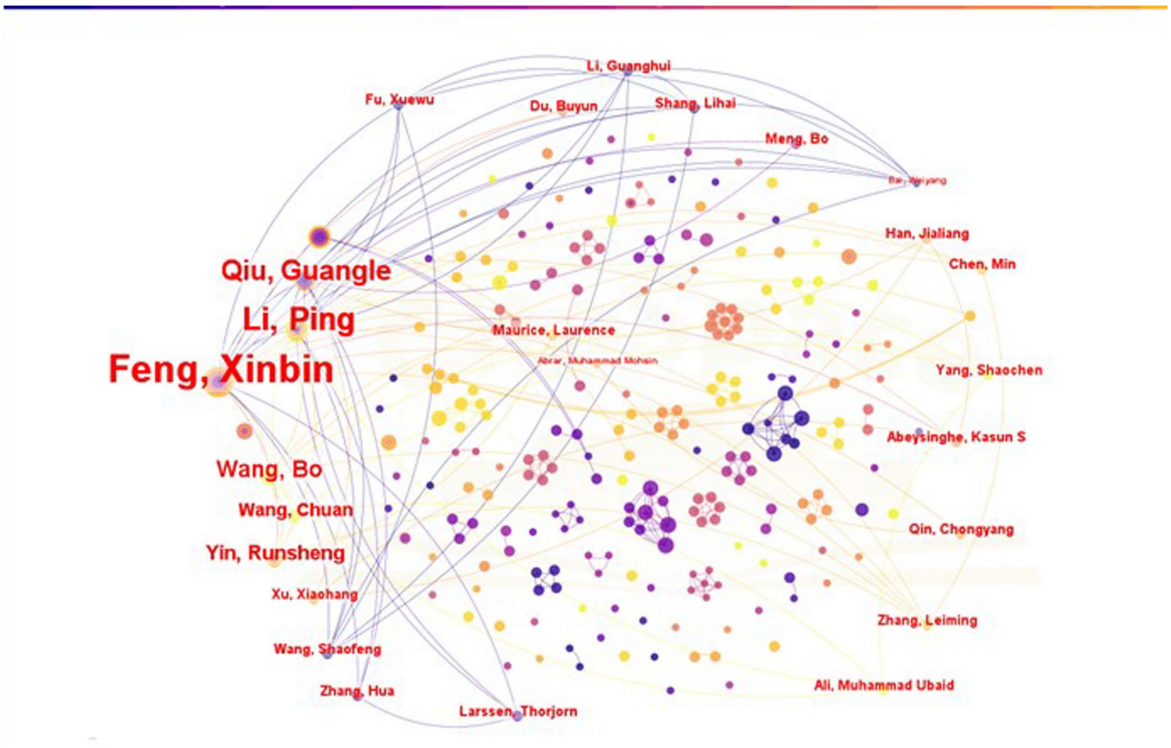

FIGURE 4
Prominent authors contributing to domestic and international journals on low-carbon agriculture and ecological co-culture models.

interest within specific fields during distinct time periods. This process helps detect emerging terms topics and trends within the field.

To further investigate the ecological co-culture model in low-carbon agriculture, this paper uses CiteSpace software for keyword clustering. The keyword cluster analysis, based on co-occurrence analysis, applies statistical principles to achieve clustering. The node type is set as "keyword," while other parameters remain consistent with those used in this study. Using the log-likelihood ratio (LLR) selection algorithm, the keyword cluster mapping is generated from the keyword knowledge network graph. Key clusters identified include terms such as "carbon footprint," "soil," "water," "climate change," "agriculture," "life cycle assessment," "greenhouse gas emissions," "biodiversity," "culture," and "fish," with larger clusters containing more related keywords. Each cluster comprises closely related keywords, and the "Cluster Explorer" in CiteSpace is used to extract clustering labels through the LLR algorithm, one of the key methods for identifying clustering labels. This process generates a keyword co-occurrence network cluster table. CiteSpace software assigns a value to each keyword within the same cluster, selecting the most significant one to represent the category and serve as the cluster label, effectively naming the newly formed cluster. In this network, the average contour value of the cluster is crucial, as it measures the quality of the clustering results. An average contour value >0.5 generally indicates reasonable clustering, while a value exceeding 0.7 signifies that the clustering is highly reliable.

The results shown in Figure 5 indicate that the average contour value for the initial 12 clusters in the study of low-carbon agriculture and the ecological co-culture model exceeds 0.7, signifying highly reliable clustering outcomes. This further supports the selection of "low-carbon agriculture and ecological co-culture model" as the article's title. Notably, keywords such as "carbon footprint," "soil," "water," "climate change," "agriculture," "life cycle assessment," "greenhouse gas emissions," "biodiversity," "culture," and "fish" are all highly relevant to the research topic. Likewise, other clustering labels reflect closely related topics.

As can be seen from Figure 5, the phenomenon of cross-cutting research themes in various clusters can be roughly summarized into seven aspects: "ecological co-culture," "rice-fish-duck," "rice-fish," "fruit tree + poultry ecological co-culture," "vineyard nesting poultry," "three-dimensional farming," and "low-carbon agriculture" areas, reinforcing the study's focus.

The analysis also highlights the role of greenhouse gas emissions, with keywords such as "food security," "ecosystem services," "agricultural carbon emissions," and "green finance" appearing particularly important. In China's agricultural sector, the growing concern for research on greenhouse gas emissions has attracted a great deal of attention from the government. The involvement of relevant forms of green finance and other forms of participation can better promote the sustainable landing of agriculture and the realization of low-carbon production, which well promotes the development of policies to achieve carbon neutrality in agriculture, and also reflects the national commitment to address carbon emissions in agriculture. Overall, in any historical period, the patterns of production and consumption provide insights into the alignment between science, technology, and the economy, justifying their continued relevance (Yang et al., 2010).

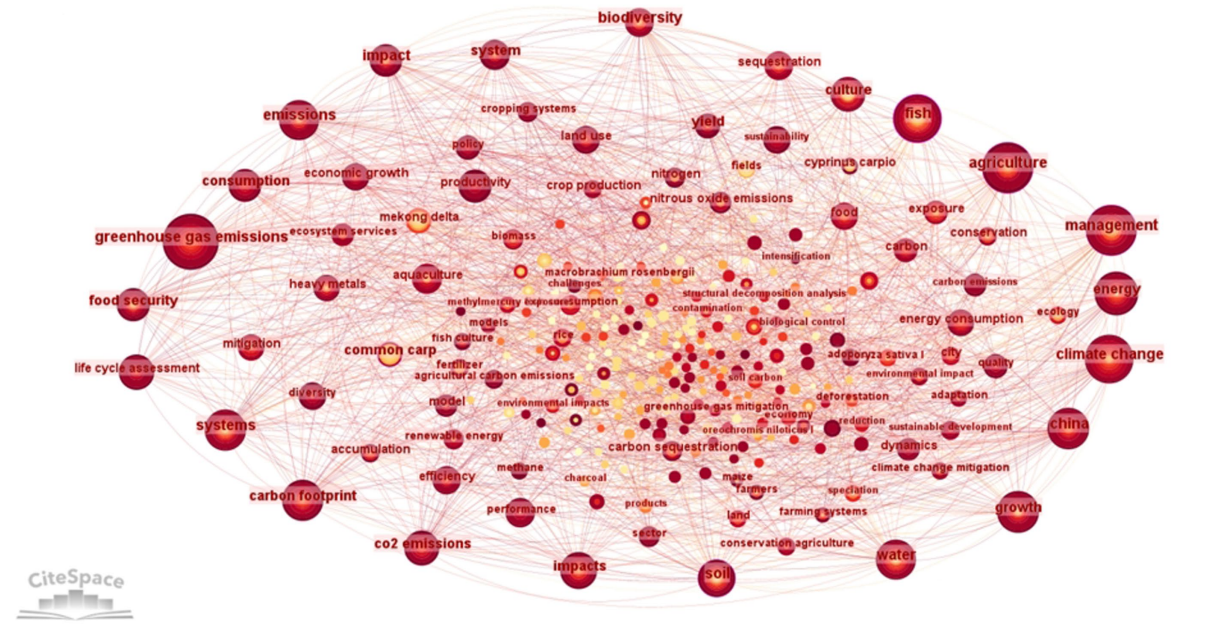

FIGURE 5
Keyword clustering analysis within the context of low-carbon agriculture and ecological co-culture models.

3.3.2 Keyword frequency analysis

In the keyword frequency analysis, CiteSpace offers tools to detect significant changes in the frequency of references over a certain period (Wang and Zhang, 2021; Hu and Jing, 2021). This detection, known as burst detection, highlights highly active fields of research, enabling the identification of emerging or transient trends. Burst detection also provides an accurate visualization of academic research hotspots, both domestically and internationally. The prominence of certain keywords can help indicate the direction of research, with more frequent terms signifying areas of greater research focus. Between 2008 and 2023, the analysis shown in Figures 6, 7 reveals that the length of the red part reflects the duration of keyword occurrence. From Figure 6, it is evident that the keywords with the highest burst intensity between 2014 and 2023 include terms such as "rice," "rice-fish symbiosis," and "ecological co-culture," with peak intensity value reaching 10.32.This indicates that at this stage, although the epidemic period has been crossed, eco-agriculture is in a progressive stage of development, and the derived eco-development model will be advanced more quickly. Additionally, keywords such as "rural revitalization" and "low-carbon agricultural technology" also garnered significant attention, with a peak intensity of 4.8. As low-carbon agriculture continues to develop in the post-pandemic era, the ecological co-culture model has shown considerable evolution. However, there remains significant potential for further research in these areas, particularly in international literature.

3.3.3 Keyword periodic change analysis

The keyword timing chart provides insights into the evolving research trends over time. This chart is generated using CiteSpace software based on keyword co-occurrence analysis for different periods (Figure 8). The evolution of keywords across time periods highlights that research on low-carbon agriculture and ecological co-culture can be divided into three distinct phases: the foundation stage, the prosperity stage, and the evolutionary development stage. As shown in Figure 8, each stage reflects shifts in academic focus, both domestically and internationally.

1 Foundation stage (2008–2010): during this period, research progressed from focusing on topics such as "fish," "soil," and "water" to incorporating keywords like "carbon footprint," "climate change," "sequestration," "food security," and "ecological rice management." At this stage, low-carbon agriculture research in China was still in its early development phase, laying the groundwork for future exploration.
2 Prosperity stage (2010–2015): in this phase, research on low-carbon agriculture and ecological co-culture in China began to focus more on "CO_2 emissions," "agricultural reserves," "terrestrial carbon emissions," and "renewable energy." Sustainable development became a core research theme, with growing attention paid to the intersection of ecological agriculture and energy. The integration of modern technology with low-carbon agriculture led to breakthroughs in this field, as researchers sought to strengthen the link between sustainability and energy.
3 Evolutionary development stage (2015–2023): in September 2020, during the 75th session of the United Nations General Assembly, China pledged to peak carbon emissions by 2030 and achieve carbon neutrality by 2060. In this stage, keywords such as "dynamic diversity," "carbon emissions," "life cycle assessment," and "fishery culture" began to gain prominence. This phase reflects the increasing relevance of energy transformation and environmental changes in the

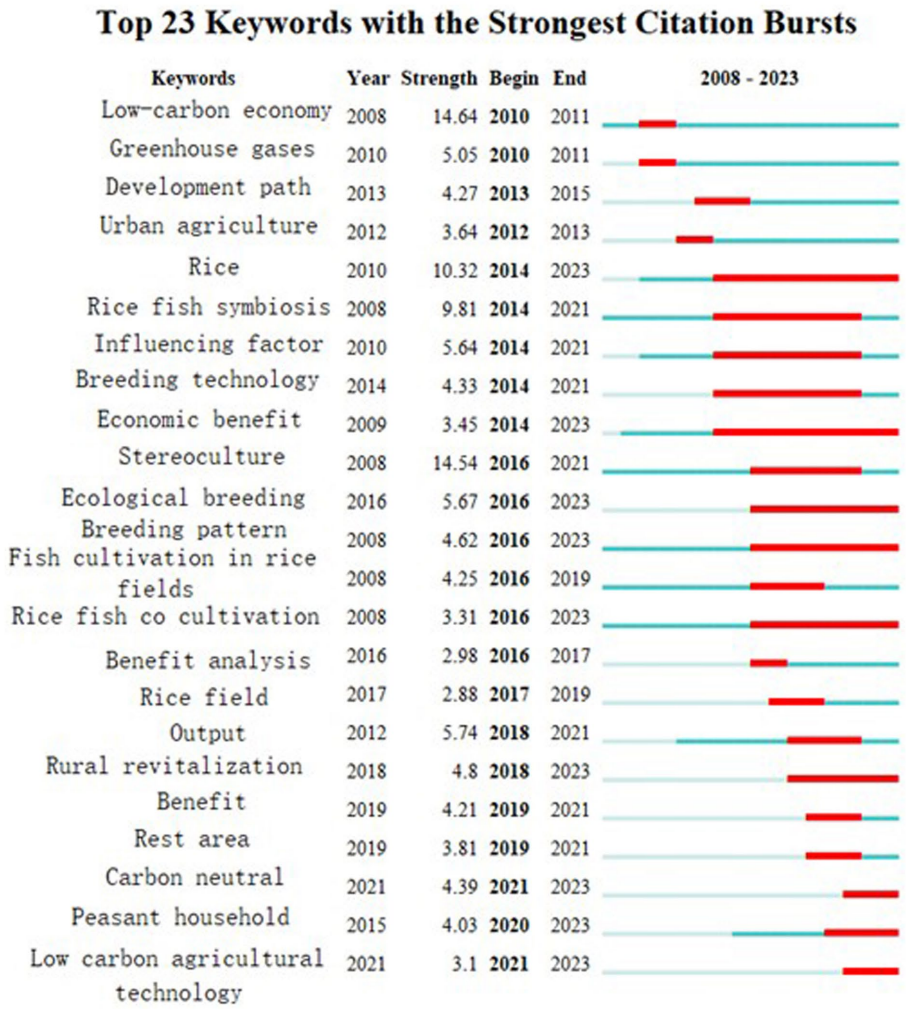

FIGURE 6
Keywords associated with low-carbon agriculture and ecological co-culture models in China.

agricultural sector, aligning with the two-carbon strategy. By integrating low-carbon agriculture with ecological co-culture, the agricultural field can better contribute to energy transition and environmental sustainability. At the same time, the huge impacts of the epidemics in this period on the economic, social and agricultural production sectors can also be better buffered in the domestic low-carbon agricultural transition and upgrading, thus better achieving social sustainability.

4 Discussion

The discussion presented in this paper synthesizes key findings on the literature surrounding low-carbon agriculture and ecological co-culture models, based on analyses of major research institutions, prominent research hotspots, and significant research progress. One of the key limitations in this study is that it primarily focuses on literature pertaining to low-carbon agriculture and ecological co-culture models without considering the number of citations-a limitation inherent to the CiteSpace software used. Future research will need to address this gap by incorporating a more comprehensive analysis of global literature on low-carbon agriculture and ecological co-culture models, including citation counts. Additionally, China's future research trajectory will likely continue to emphasize on rice cultivation, rice-fish symbiosis, and ecological co-culture. This reflects a shift in scholarly perspectives toward integrating concepts of low-carbon economies, carbon neutrality, and innovative rice-fish symbiosis models. The growing attention and research on rice-fish symbiosis and ecological co-culture models can significantly enhance the integration of industry, academia, and research, fostering collaborative advancements. This progress also supports the continuous refinement and adaptation of agricultural policies and practices, aligning them with sustainable development goals.

A broader review of both domestic and international literature on low-carbon agriculture and ecological co-culture models indicates that the development of low-carbon agriculture has progressed over a substantial time span. During this period, various topics such as "ecological co-farming," "rice-fish-duck," "rice-fish," "fruit tree + poultry ecological co-culture," "vineyard nesting poultry," "three-dimensional farming," and "low-carbon agriculture" have been actively researched and refined. However, it is crucial to recognize that

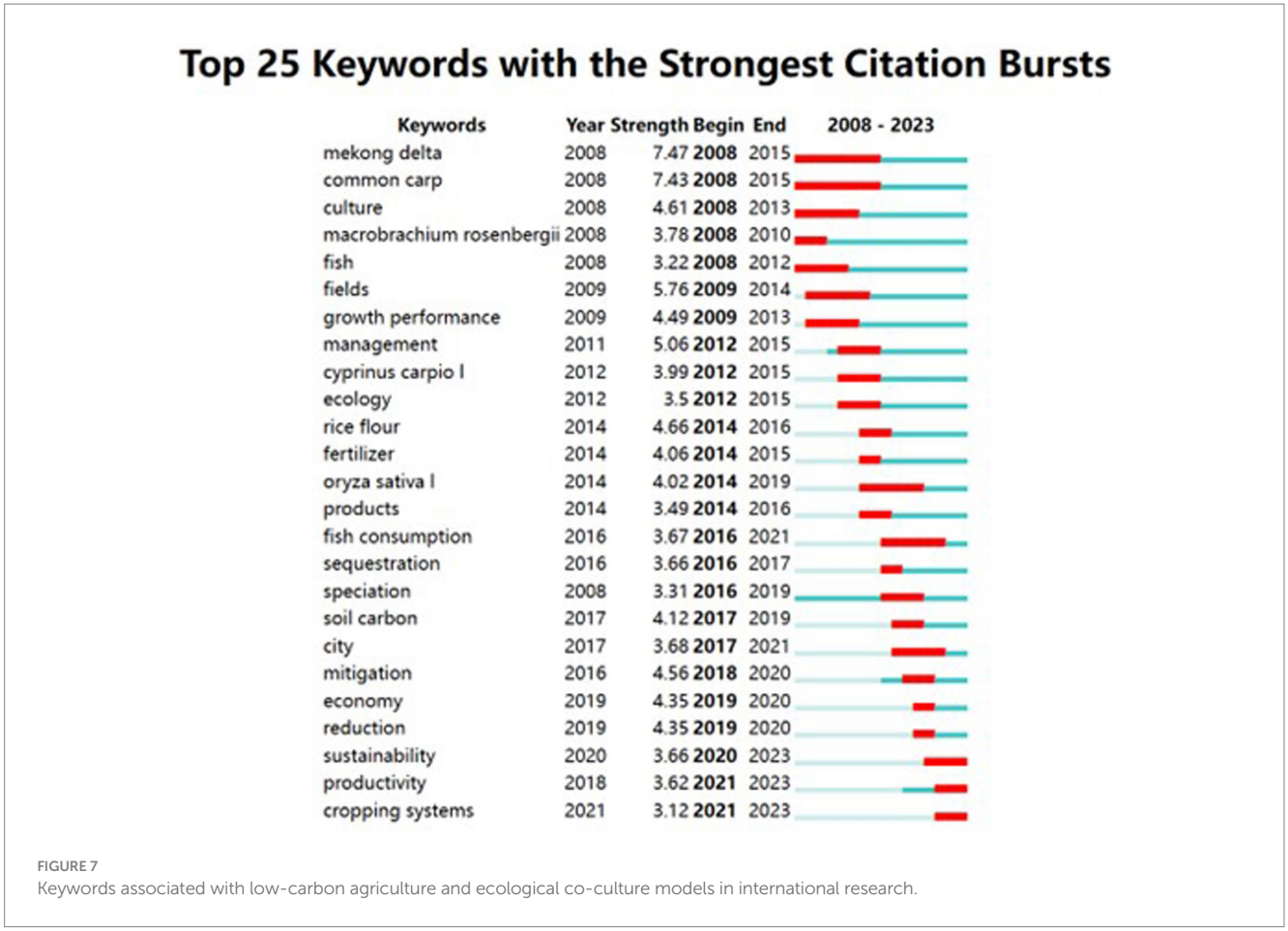

FIGURE 7
Keywords associated with low-carbon agriculture and ecological co-culture models in international research.

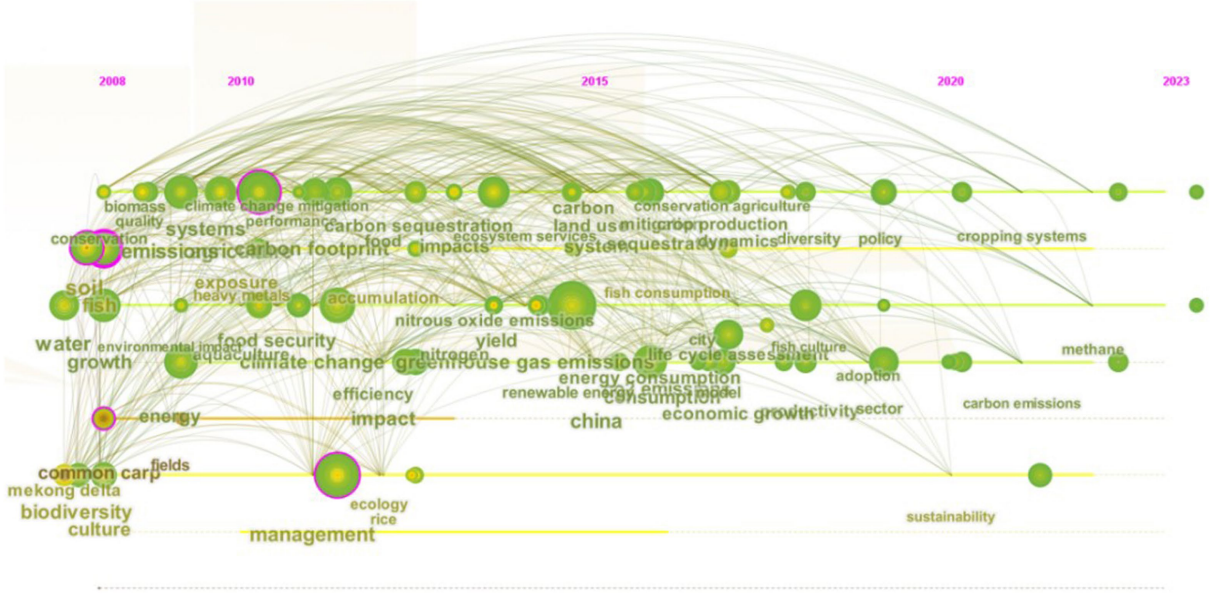

FIGURE 8
Periodicity and trends in keywords related to low-carbon agriculture and ecological co-culture models in international research.

the development of low-carbon agriculture cannot be solely classified as the development and innovation of the agricultural sector. Instead, it should be understood as the comprehensive application of interdisciplinary knowledge, requiring innovative organizational

models and mechanisms to effectively address the challenges of energy use and environmental sustainability in agriculture. Future research should leverage both Chinese and international literature databases, such as the CNKI and the WOS Core Collection, as primary platforms for literature retrieval and sample data sources. CiteSpace visual measurement software should further be applied to systematically analyze research on low-carbon agriculture and ecological co-culture models domestically and internationally. This approach aims to enhance and deepen understanding of the relationship between agricultural practices and energy utilization, providing a comprehensive view of how these systems contribute to sustainable development.

Although CiteSpace software is widely applied in bibliometric research, it has certain limitations, such as its inability to distinguish between the first author and the corresponding author in citation analysis. To address this, tools such as HistCite and VOSviewer could be employed to achieve a more comprehensive and systematic examination of the research content. In addition, potential biases in keyword selection or the scope of the database used remain challenging to avoid. Despite these limitations, this study is grounded in objective literature data, ensuring the reliability of the results. Therefore, the conclusions drawn from this paper hold substantial theoretical value and offer important reference points for understanding the research status and cutting-edge developments in low-carbon agriculture and energy utilization. In future research, efforts will continue to focus on the small scale ecological co-culture model, using field research data as a foundation to achieve multidisciplinary integration.

5 Conclusion

This paper utilized the CNKI database and the WOS Core Collection as platforms for literature retrieval. Keywords such as "ecological co-culture," "rice-fish-duck," "rice-fish," "fruit tree + poultry ecological co-culture," "vineyard nesting poultry," "three-dimensional farming," and "low-carbon agriculture" were used for fuzzy searches, with the data retrieval period set from 2008 to 2023 to identify relevant academic journal papers. Using CiteSpace software, this study mapped the research landscape on low-carbon agriculture and ecological co-culture models, systematically analyzing the contributions of major research institutions, prominent authors, and research hotspots. The findings of this study reveal several key points regarding the status of research of low-carbon agriculture and ecological co-culture models both domestically and internationally:

Basic characteristics of the literature: The number of published articles on "ecological symbiosis" and the "rice-fish-duck" model from 2014 to 2023 has demonstrated a steady increase. Research on the "rice-fish" model has demonstrated clear growth, with an average of 58 journal articles published annually between 2010 and 2023. Similarly, publications on "low-carbon agriculture" have increased substantially since 2010, with yearly publications ranging from 100 to 300. In the WOS Core Collection, the number of articles on "rice-fish" research ranged from 104 to 273 during the period 2008–2023, with an average of one article per year. Meanwhile, the number of articles on "low-carbon agriculture" was relatively low between 2011 and 2023, peaking in 2022 with 144 publications-the highest in recent years. Notably, there are distinct differences and similarities between the research on "poultry farming in vineyards" and "vertical farming" both domestically and internationally. The similarity lies in the fact that no scholar has studied the ecological co-culture model of "poultry farming in vineyards" from 2008 to 2023, revealing a remarkable research gap. The difference, however, is that domestic scholars have shown higher research input and output than their international counterparts in the area of "vertical farming." Overall, the relationship between low-carbon agriculture and ecological symbiosis has garnered extensive attention from scholars due to its considerable development potential. However, gaps remain in the research, particularly regarding new models such as rice-fish co-culture and poultry integration, suggesting an opportunity for future studies to explore these innovative approaches further.

Main research institutions and authors: Analysis using CiteSpace software identifies 272 nodes and 421 connections, with a network density of 0.0114, indicating a relatively dispersed yet interconnected research landscape. The primary research institutions are centered around universities and research institutes specializing in agricultural and life sciences, such as China Agricultural University and the Institute of Geographic Sciences and Natural Resources Research under the Chinese Academy of Sciences. These institutions lead the field, and there is considerable similarity in the focus of both domestic and international research institutions. Among the authors, prominent scholars such as Min Qingwen, Chen Xin, Cheng Shengkui, and Huang Huang have established themselves as leaders in the field, with their research teams holding a distinct advantage in terms of contribution and influence. The analysis reveals 255 authors and 319 connections, with a network density of 0.0099, demonstrating a growing field with substantial potential for further research on low-carbon agriculture and ecological symbiosis in China. The collaboration networks between authors are robust, highlighting the strong cooperative relationships and active exchanges of ideas that characterize research in this area.

Research hotspots: Keyword clustering and outbreak intensity analysis from 2014 to 2023 indicate significant research activity in specific areas of low-carbon agriculture and ecological co-culture models. The most prominent keywords include "rice," "rice-fish symbiosis," and "ecological co-culture," with peak intensity values reaching as high as 10.32. Keywords such as "rural revitalization" and "low-carbon agricultural technology" also saw notable peaks in attention, with a peak intensity of 4.8. Other frequently occurring terms include "carbon footprint," "soil," "water," "climate change," "agriculture," "greenhouse gas emissions," "biodiversity," and "fish." From keyword clustering analysis, with contour values exceeding 0.7 for the top 12 clusters, it becomes clear that research on low-carbon agriculture and ecological co-culture models has evolved periodically. Early topics centered around three-dimensional farming and rice-fish symbiosis, while more recent research has increasingly shifted toward food security and green finance, particularly in the context of carbon peak and carbon neutrality. Similarly, international research has transitioned from focusing on food safety to examining genetic diversity and other emerging topics. Examples include the classification of species of the genus Geranium in Australia, studies on the genetic diversity of wheat in Mexico, and the exploration of patterns of genetic diversity in endangered corals. Moreover, there is notable interdisciplinary overlap in research related to low-carbon agriculture and ecological co-culture, which can be summarized into three main areas: "low-carbon agriculture," "rice-fish co-cultivation," and "ecological energy."

Low-carbon agriculture has emerged as a critical area of focus in response to global warming and the global push for energy transition. Governments worldwide are prioritizing the development and implementation of low-carbon energy strategies to increase investment in low-carbon energy, with China placing particular emphasis on research into agricultural carbon emissions as a key component of its environmental policies. The rice-fish co-culture model, with its long history, remains a central topic of research. Ecological energy is also gaining prominence within the broader framework of energy transition.

The impact of COVID-19 has highlighted the need for high-quality sustainable development in agricultural production and food security in the post-pandemic era. Achieving high-quality agricultural development of agriculture will be crucial in reducing global dependence on energy consumption globally, accelerating the transition to low-carbon energy, and meeting carbon neutrality goals. In turn, a green and low-carbon energy structure will further support the sustainable development of agriculture by minimizing its environmental footprint. The ecological symbiosis model in low-carbon agriculture remains an important area of research both at home and abroad. Given its potential to enhance sustainability while addressing environmental challenges, this model deserves continued research. This paper is based on a combination of agroecosystem theory and bibliometrics to systematically analyse the low-carbon mechanisms and multidimensional benefits of the ecological symbiosis model, and to provide a scientific basis for solving the "double-lock" dilemma of emissions reduction and food security in agriculture. Future research can further combine artificial intelligence (e.g., carbon flux monitoring by drones) and blockchain (e.g., carbon footprint traceability) to promote the upgrading of low-carbon agriculture toward intelligence and verifiability, and explore the combination of ecological co-culture practices and innovative energy solutions to further promote the sustainable development of global agriculture.

Author contributions

XL: Conceptualization, Data curation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

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