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Research progress on fertilizer carbon emissions: a bibliometric analysis (2008–2024)

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Fertilizers are a major source of agricultural carbon emissions, yet fertilizer carbon emissions (FCE) research remains fragmented and lacks systematic overview, despite its importance for climate mitigation. This paper selects 2,494 related literature in the Web of Science from 2008 to 2024. It reveals the research hotspots and development trends in the field of FCE based on CiteSpace. The results show that: (1) The number of published papers in this field has shown an exponential upward trend, which can be divided into three stages: the infancy stage, the steady development stage, and the rapid growth stage of research. (2) China and the United States emerge as dominant contributors, reflecting their dual roles as major emitters and key drivers of scientific innovation. While high-yield authors form tight collaboration clusters, overall author cooperation remains limited, suggesting the need for greater cross-institutional and interdisciplinary synergy. (3) Co-citation and keyword analyses indicate that the dominant research hotspots include nitrous oxide emissions, fertilizer types, soil carbon cycles, and life-cycle carbon footprint assessment. Cluster and burst analyses reveal a growing emphasis on precision agriculture, emission reduction strategies, and sustainable soil management. This study outlines the trajectory and key areas of focus in FCE research, providing theoretical and methodological support for advancing regenerative agriculture and achieving a low-carbon agricultural transformation. The findings provide a valuable reference for scholars, policymakers, and practitioners seeking to enhance emission reduction strategies and promote sustainable land use globally.

KEYWORDS

fertilizer carbon emissions, research progress, knowledge mapping, research theme evolution, international comparison

1 Introduction

Global warming has become one of the most significant challenges facing the world today, exerting a profound impact on various aspects, including the balance of the ecosystem and the development of human society (Lashof and Ahuja, 1990; Al-Ghussain, 2019). According to the latest Intergovernmental Panel on Climate Change (IPCC) report, the global average temperature has increased by approximately 1.1°C over the past century (Bongaarts, 2024). As the dominant factor driving the rise in temperature, carbon emissions have received significant attention from all sectors of society (Florides and Christodoulides, 2009; Fang et al., 2011; Deng et al., 2021). Meanwhile, early data from this institution indicate that agriculture (including crop and livestock production, forestry, and

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related land-use changes) accounts for a significant proportion of anthropogenic greenhouse gas emissions, as high as 30% (Tubiello et al., 2013). Given its close connection with the foundation of human existence, the importance of agricultural carbon emissions cannot be ignored.

In agricultural production, a large amount of fertilizer is used. The carbon emissions generated in producing, transporting, and applying fertilizers have a profound impact on the global and climate-carbon cycle systems. As an important agricultural production input, on the one hand, the production, transportation, and use of fertilizers consume a significant amount of energy and generate greenhouse gas emissions, making them a substantial source of carbon emissions. On the other hand, more importantly, after the application of fertilizers, it is likely to change the properties of the soil, affect the growth and development of crops and the composition of soil microorganisms, and regulate the fate of nutrients in products, enabling more nutrients to be absorbed by crops and retained in the soil nutrient pool, thus reducing soil carbon emissions (Edmeades, 2003; Williams et al., 2013).

Over the past few decades, the global application of chemical fertilizers has continued to increase in response to the food pressure resulting from the rapid growth of the global population. Taking nitrogen fertilizers as an example, in the 1960s, the average nitrogen application rate on global cultivated land was 44.6 kg/ha. In comparison, in the 21st century, the average nitrogen application rate had increased to 100.9 kg/ha, a total increase of 2.26 times (Adalibieke et al., 2023). Relevant studies have shown that, on average, 1 ton of nitrogen fertilizer generates 2.12 tons of carbon dioxide equivalent to carbon emissions (Sistani et al., 2011; Xu et al., 2022). Meanwhile, long-term application of inorganic fertilizers also causes many problems for soil health. Soil components are common. The excessive application of fertilizers causes the pores between soil particles to become smaller, resulting in poor soil aeration and water permeability. As a result, the crop root system is impeded due to a lack of oxygen, and growth is hindered (Li C. Z. et al., 2020). For another, the problem of soil acidification becomes prominent. The acidic soil environment caused by fertilizer application inhibits the activities of beneficial microorganisms in the soil, and the number of microbial communities that could have helped plants fix nutrients and resist diseases decreases sharply (Wang et al., 2023a; Van Leeuwen et al., 2019). These problems not only affect crop yields but also lead to a continuous decline in land productivity. Therefore, accurately grasping the research trends of FCE is of great practical significance for formulating scientific and reasonable emission reduction strategies, promoting the development of regenerative agriculture, and maintaining the stability of the soil ecosystem.

Given the importance of the FCE problem, many scholars have engaged in research in this field. Regarding the quantitative evaluation of FCE, based on the life cycle theory, scholars have mainly conducted in-depth explorations of the two aspects of fertilizer production and application (Wu et al., 2021). The emission factor method is commonly used for quantitative assessment in the fertilizer production process (Wood and Cowie, 2004). For example, West and Marland (2002) conducted a comprehensive analysis of the carbon cycle of agricultural inputs in the United States. They calculated the implicit carbon emission coefficients of various fertilizers throughout their life cycles. Zhang et al. (2013) calculated the fertilizer carbon emission coefficients using data from 230 fertilizer plants in China. They quantified the carbon footprint of China's nitrogen fertilizer production and consumption chain.

However, current research faces the problem of data collection. When calculating carbon emissions, the actual differences among countries are not fully considered, which may lead to deviations, and the research's precision still has room for improvement. The field experiment and the mathematical model methods are the leading accounting methods in the fertilizer application process. The field experiment method utilizes static chambers to collect data for calculating carbon emissions, focusing on the fertilizer application process and involving indicators such as the properties of the sampling chambers and the amount of fertilizer use (Correa et al., 2021; Chi et al., 2020). The mathematical model method integrates the carbon emission factors of crops to construct a model for calculation, which can measure indirect emissions and cover multiple links such as fertilizer production, transportation, and application. Therefore, its accuracy is affected by regional natural, agricultural, and socio-economic differences (Yao et al., 2023).

Regarding the factors influencing FCE, scholars have mainly researched three dimensions: fertilizer types, fertilizer additives, and farmland management. In terms of fertilizer types, compared to traditional chemical fertilizers, controlled-release fertilizers can reduce agricultural greenhouse gas emissions caused by conventional fertilization in agricultural production (Guo et al., 2022; Sikora et al., 2020). Additionally, different types of organic fertilizers also emit varying amounts of greenhouse gases during their composting processes (Li et al., 2023). In terms of fertilizer additives, many studies have shown that by adding zeolite and biochar to chemical fertilizers, the soil environment can be effectively improved, leading to changes in the structure of the microbial community related to carbon emissions and thus reducing agricultural carbon emissions (Ferretti et al., 2017; Geng et al., 2024). For farmland management, water management, and tillage methods are important factors affecting agricultural carbon emissions. Appropriate water is conducive to the transformation and absorption of fertilizer nutrients. It reduces carbon emissions, while no-till treatment also promotes the maintenance of soil carbon sequestration and thus reduces agricultural carbon emissions (Ozlu et al., 2022; Bhattacharyya et al., 2022).

Although existing studies have contributed to research in FCE from multiple dimensions, it is worth noting that, while relevant research is continuously advancing, few types of literature systematically synthesize the progress of research in this field. To fill this gap, this study conducts a bibliometric analysis of 2,494 publications from the Web of Science (2008–2024) using CiteSpace. By mapping intellectual networks and frontier themes, this study contributes to the academic understanding of FCE in three ways: (1) It provides a comprehensive overview of global FCE research from 2008 to 2024, clarifying its temporal evolution, disciplinary structure, and collaborative dynamics within the field. (2) It distills thematic hotspots and emerging research frontiers in the field, thereby informing future scholarly agendas and climate-oriented policy formulation. (3) It explores key analytical mechanisms, identifies existing research gaps and proposes actionable recommendations to advance future studies in the field.

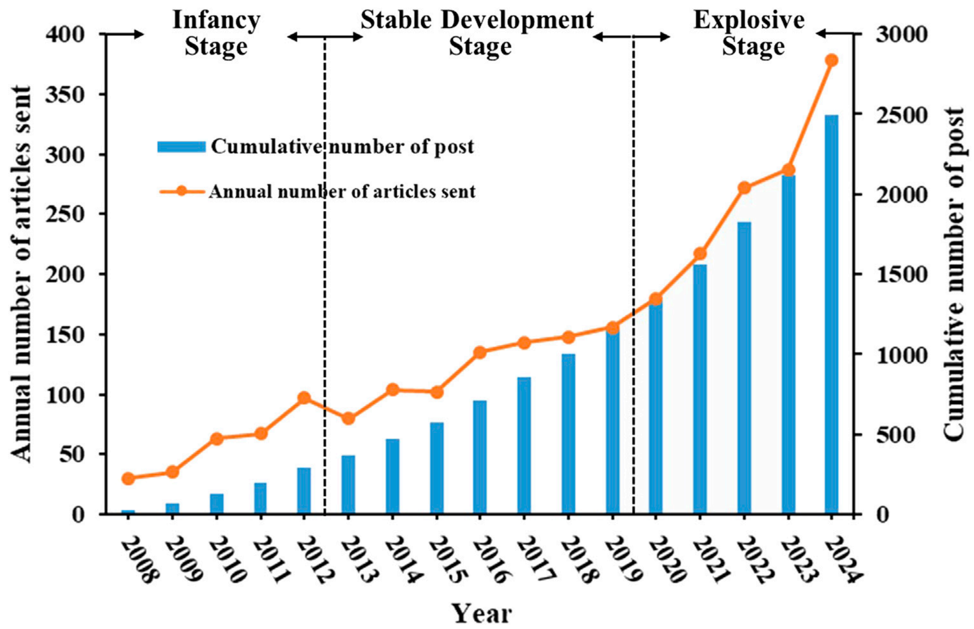

FIGURE 1
Changes in annual and cumulative number of FCE publications from 2008 to 2024.

2 Materials and research tools

2.1 Data source

This paper conducts a quantitative analysis using English-language literature. The data samples are selected from the Web of Science database. This database includes important literature from various disciplines worldwide, authors, and affiliated institutions, and provides complete citation information. Specifically, the database is set to the Web of Science, and the citation indexes selected are "Science Citation Index Expanded (SCI-EXPANDED) -- 1900-present" and "Social Sciences Citation Index (SSCI) -- 1900-present".

The database retrieval criteria are as follows: Topic (fertilizer carbon emissions). The retrieval period was set from 1 January 2008, to 31 December 2024, to ensure that key research achievements at all stages are covered. After strict duplication, screening, and format conversion, a high-quality literature dataset is constructed, laying a solid data foundation for subsequent accurate analysis. Finally, 2,494 English-language articles are selected for bibliometric analysis. The data is downloaded in the "Full Record and Cited References" format and saved as a plain text file as the data sample for analysis.

2.2 Research tools

This paper employs bibliometric analysis and creates a knowledge map using CiteSpace software. Drawing a knowledge map is to intuitively display the most cutting-edge fields of knowledge and information in a visual image format (Wu et al., 2024). CiteSpace is a scientific literature data visualization software that can create knowledge maps of disciplines or knowledge domains, identify hotspots and frontier issues, and has broad application value in academic research (Chen, 2012). This paper comprehensively uses Citespace 6.4.R1 and Excel to explore the publication and cooperation network of research on FCE and its development trends. By setting the node types in CiteSpace as "Country," "Author," "Cited Literature," and "Keyword," etc., the time distribution and author distribution of the literature are systematically sorted out, and further analysis methods such as keyword analysis and co-citation analysis are used to intuitively display the research frontiers and hot trends in this field.

3 Results

3.1 Analysis of annual publication

The annual distribution map of literature can fully reflect the changes in the number of publications and the development speed in FCE within a specific time frame, allowing for the exploration of research trends and chronological laws in this field. As shown in Figure 1, since 2008, the annual number of publications and the total number of publications on FCE have shown the exponential growth trend. This paper utilizes Excel to conduct statistical data analysis and employs the built-in exponential function calculation to verify the results further. Through statistical regression, the regression function of the annual number of publications is $Y = 35.16 \times e^{0.14X}$, with a correlation coefficient of $R^2 = 0.948$, and the regression function of the total number of publications is $Y = 61.56 \times e^{0.24X}$, with a correlation coefficient of $R^2 = 0.918$. The fitting effect is excellent, and the exponential growth trend is verified, fully confirming the value and potential of the field of FCE in today's era.

Research on fertilizer carbon emissions can be divided into three phases based on variations in the number of annual publications.

TABLE 1 Top 10 countries by number of publications.

Ranking	Country	Number of articles	Intermediary centrality
1	China	1,099	0.19
2	United States	430	0.22
3	Germany	189	0.23
4	Australia	185	0.09
5	Canada	150	0.12
6	England	126	0.04
7	India	121	0.05
8	Japan	95	0.11
9	Italy	84	0.13
10	Spain	83	0.03

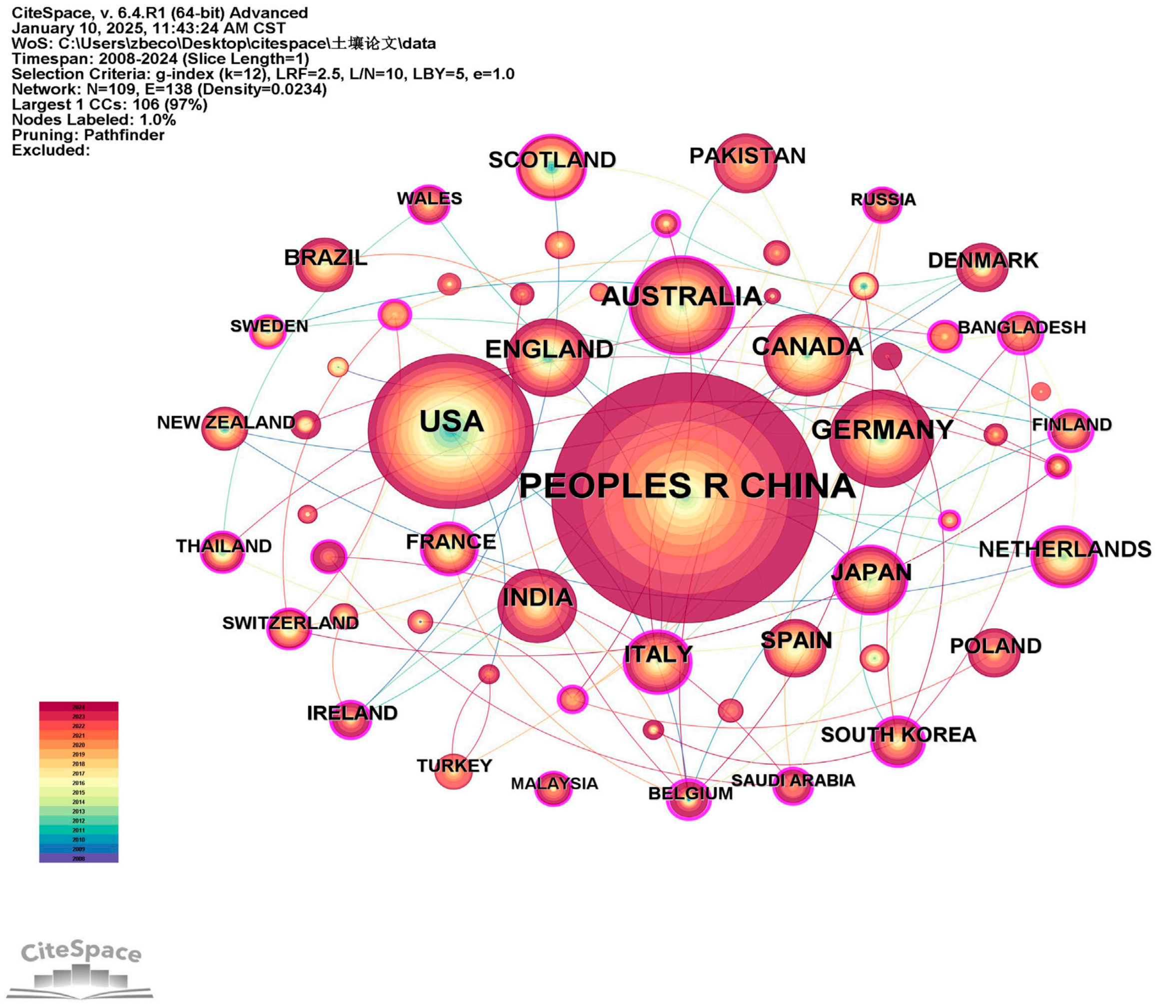

FIGURE 2
Collaboration network map of countries/regions.

The division method is logically consistent with the staging of research reviews in the field of agricultural by Wu et al. (2024) and Hu et al. (2024), and has some theoretical basis: (1) Infancy stage (2008–2011): There were few relevant studies in this stage, and the research was in its infancy, with an average annual number of publications of about 48. Moreover, the research topics were lacking in richness, primarily focusing on the greenhouse gas emissions of fertilizers against the backdrop of global warming. (2) Stable development stage (2011–2019): Although the number of relevant research publications fluctuated in this stage, it showed an overall relatively stable growth trend, with an average annual number of publications of about 121. With the gradual deepening of the research, the research perspective in this field has been broadened to encompass the entire life cycle, and the research boundary has been expanded to include hot topics such as soil organic carbon and crop straws. (3) Rapid growth stage (2019–2024): Since 2019, the annual number of publications has shown rapid growth, with an average annual growth rate of more than 20% and an average annual number of publications of about 267, mainly focusing on articles related to the mechanism of carbon emissions, carbon balance, and the green benefits of fertilizers.

3.2 Analysis of countries and authors

We use CiteSpace to visually analyze the countries where the sample literature was published. It obtains the co-occurrence map of countries that published articles on FCE from 2008 to 2024, along with statistical data on the number of publications from high-yielding countries (Table 1). Countries with less than 20 publications are omitted from the map to ensure clarity. Figure 2 shows the number of nodes N = 109, the number of connections E = 138, and the network density Density = 0.0234. From 2008 to 2024, 109 countries participated in research on FCE. Most countries have relatively close and diverse connections, and the cooperation network shows a trend of dynamic expansion and deepening. However, some countries also have relatively sparse connections or no connections.

The top three countries in terms of the number of publications are China (1,099 articles), the United States (430 articles), and Germany (189 articles). These countries are also among the top ten carbon-emitting countries in the world. Many publications from these countries indicate that they are actively researching FCE to address the adverse effects of high carbon emissions and explore effective strategies to reduce greenhouse gas emissions. Especially in China and the United States, it demonstrates their strong sense of responsibility in the global field of environmental scientific research.

Following China's accession to the WTO in 2001, it experienced a rapid increase in carbon dioxide emissions while achieving significant economic growth. In 2007, China surpassed the United States to become the world's largest carbon emitter. In recent years, China has attached great importance to the issue of carbon emissions and proposed the policy goal of achieving carbon neutrality by 2060, indicating China's determination to actively respond to climate change and promote green and low-carbon development. Moreover, remarkable results have been achieved, and emissions have gradually stabilized. According to current scenario predictions, China's carbon dioxide emissions are expected to decrease by 72% by 2050 (Cail and Criqui, 2021).

The United States has also set greenhouse gas emission reduction targets, proposing a target of reducing emissions by "26%–28%" compared to the 2005 emission level by 2025. According to the 2023 World Energy Statistical Review, the United States has seen the most significant decline in carbon dioxide equivalent emissions over the past 15 years, a reduction of 879 million metric tons, or 14%. However, the United States is still the world's second-largest greenhouse gas emitter. Although its emission reduction efforts have made progress, its emissions are still higher than those of many other countries. In terms of specific data, in 2022, the *per capita* emissions of residents in the United States were nearly 15 metric tons of carbon dioxide, while the *per capita* emissions of residents in China were less than 9 metric tons. Therefore, the United States has achieved some results in emission reduction, but it still faces challenges and needs to continue working hard to achieve deeper emission reductions and address the impacts of climate change.

We also conducted a visual analysis of the authors of the sample literature. We obtained the co-occurrence map of the authors who published articles on FCE from 2008 to 2024. Figure 3 shows the number of nodes N = 366, the number of connections E = 427, and the network density Density = 0.0064. From 2008 to 2024, 366 authors appeared in the field of FCE. At the same time, the cooperation network structure in this field includes research teams with multiple connections, pairwise cooperation relationships with single connections, and individual authors without connections.

Most scholars in this field are individual authors without connections, and only the closely connected groups of high-yielding authors are displayed on the map. According to statistics, among the 366 authors, only 8 have a centrality of 0.01 or above, and the centrality of the remaining 358 authors is 0. This further emphasizes that the cooperation relationships among most scholars still need to be deepened, and the cooperation across institutions, disciplines, and teams must also be further strengthened. However, it could be seen from the map that the network structure is tight in areas with a high network connection density, and a community of high-yielding authors has been initially formed. The connections among high-yielding authors are relatively close, and the formation of the cooperation network depends on the high-yielding authors in the middle area, highlighting the significant promoting role of high-yielding authors in the research of this field.

3.3 Co-citation analysis

Co-citation analysis is one of the most widely used methods to identify influential journals or papers in a specific academic field (Zhao et al., 2024). Chang et al. (2015) pointed out that a co-citation relationship is established when a third paper simultaneously cites two or more papers or journals. Generally, some reference papers with the most co-citations become hotspots, reflecting the knowledge base and academic trends (Sabe et al., 2023). Based on this, this paper uses CiteSpace to conduct co-citation analysis at the journal and literature levels in FCE.

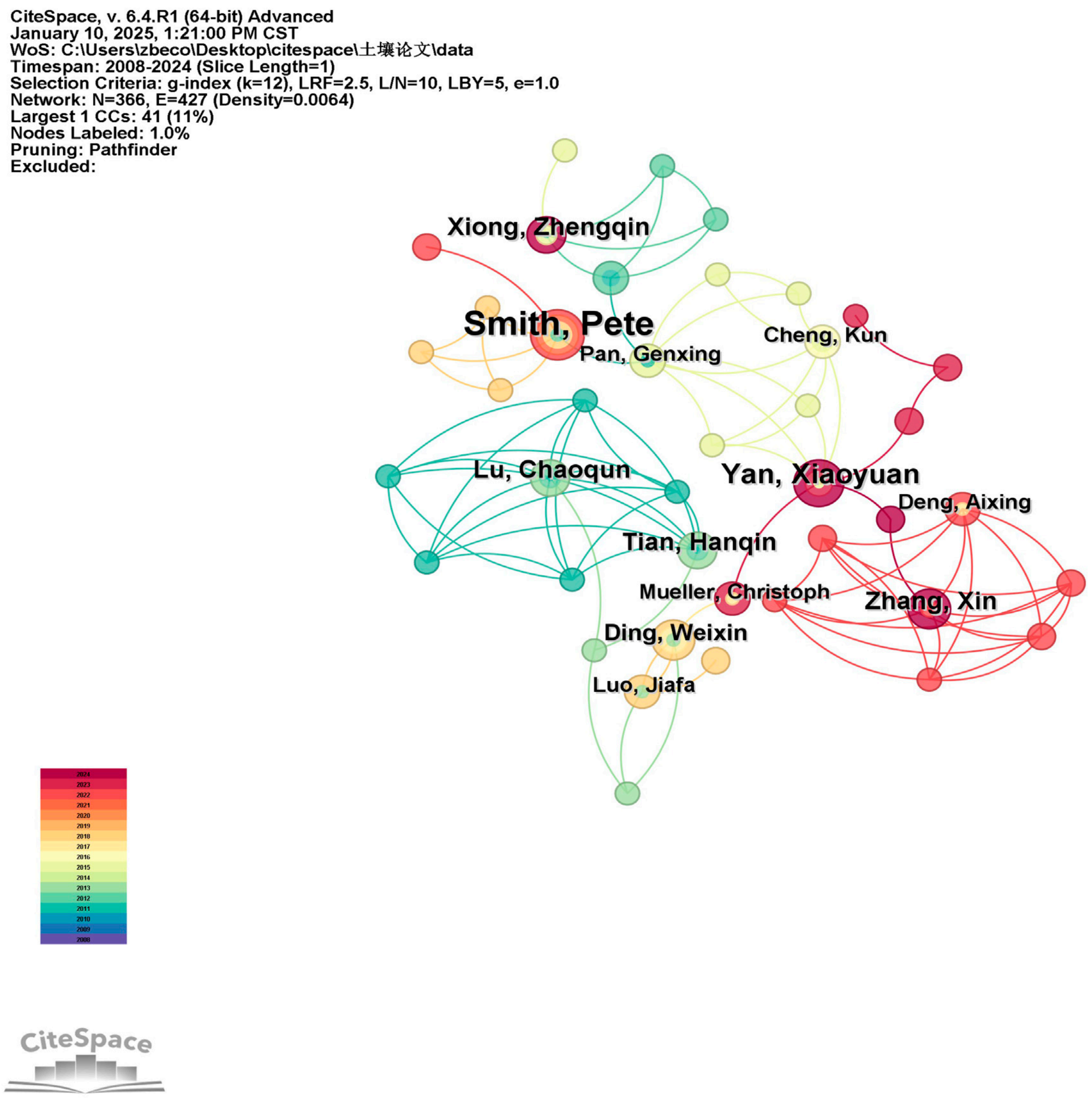

FIGURE 3
Collaboration network map of the high-yielding author.

TABLE 2 Top 10 journals regarding frequency on FCE research.

Ranking	Journal	Frequency	Centrality
1	Agriculture, Ecosystems & Environment	1,867	0.06
2	Global Change Biology	1,511	0.07
3	Soil Biology and Biochemistry	1,505	0.09
4	Science of The Total Environment	1,394	0.03
5	Plant and Soil	1,217	0.00
6	Nutrient Cycling in Agroecosystems	1,196	0.24
7	Soil Science Society of America Journal	1,156	0.07
8	Biology and Fertility of Soils	1,110	0.07
9	Soil and Tillage Research	1,098	0.01
10	Journal of Environmental Quality	1,062	0.06

TABLE 3 Top 10 authors regarding frequency on FCE research.

Ranking	Author	Frequency	Centrality	Year	Country
1	Rattan Lal	494	0.16	2008	United States
2	Pete Smith	409	0.07	2008	United Kingdom
3	Alexander F. Bouwman	335	0.01	2008	Netherlands
4	Eric A. Davidson	322	0.04	2008	United States
5	Philippe Rochette	310	0.18	2008	Canada
6	Arvin R. Mosier	277	0.07	2008	Australia
7	Keith A. Smith	216	0.07	2008	United Kingdom
8	Xia LongLong	207	0.05	2019	China
9	Jan Willem Van Groenigen	207	0.21	2008	Netherlands
10	Johannes Lehmann	200	0.18	2012	United States

TABLE 4 Top 10 literature regarding frequency on FCE research.

Ranking	Title	Citation	Year	Journal
1	Global meta-analysis of the nonlinear response of soil nitrous oxide (N_2O) emissions to fertilizer nitrogen	62	2014	*Proceedings of the National Academy of Sciences*
2	Benefits and trade-offs of replacing synthetic fertilizers by animal manures in crop production in China: A meta-analysis	55	2020	*Global change biology*
3	A comprehensive quantification of global nitrous oxide sources and sinks	54	2020	*Nature*
4	Towards an agronomic assessment of N_2O emissions: a case study for arable crops	51	2010	*European journal of soil science*
5	Global nitrous oxide emission factors from agricultural soils after addition of organic amendments: A meta-analysis	48	2017	*Agriculture, Ecosystems & Environment*
6	Stimulation of N_2O emission by manure application to agricultural soils may largely offset carbon benefits: a global meta-analysis	45	2017	*Global Change Biology*
7	Nitrous oxide emissions from soils: how well do we understand the processes and their controls?	41	2013	*Philosophical Transactions of the Royal Society B*
8	Review of greenhouse gas emissions from crop production systems and fertilizer management effects	41	2009	*Agriculture, Ecosystems & Environment*
9	Organic-substitute strategies reduced carbon and reactive nitrogen footprints and gained net ecosystem economic benefits for intensive vegetable production	34	2019	*Journal of Cleaner Production*
10	Greenhouse gas emissions intensity of global croplands	33	2017	*Nature Climate Change*

3.3.1 Journal co-citation analysis

Table 2 shows the top 10 journals ranked by the number of citations, reflecting their influence and interrelationships in this field. *Agriculture, Ecosystems & Environment* topped the list with 1,867 citations, highlighting its position as a core source of literature in the field. *Global Change Biology* and *Soil Biology and Biochemistry* follow with 1,511 and 1,505 citations respectively, playing an important role in related academic research. The literature published in these journals holds significant reference value for the field of fertilizer carbon emission research and serves as an indispensable academic resource for researchers.

3.3.2 Author co-citation analysis

Table 3 lists the 10 most cited authors in the field of FCE from 2008 to 2024. Among them, *Rattan Lal* (494), *Pete Smith* (409), *Alexander F. Bouwman* (335), *Eric A. Davidson* (322), and *Philippe Rochette* (310) are the 5 authors with the highest number of citations in the literature, which means that the academic community widely recognizes these authors and represent the most authoritative academic force in this field. Among them, *Rattan Lal* from *The Ohio State University* in the United States is the most co-cited author, whose research results had been included in the IPCC Agricultural Emission Reduction Assessment System, with 494 citations in this field in the past 17 years, making important contributions to optimizing agricultural carbon emission management at the fertilizer level. His academic achievements mention that fertilizers play a dual role in carbon emissions. They not only consume energy and generate carbon emissions but also enhance the carbon sequestration capacity of crops, thereby reducing carbon emissions. Through effective fertilizer management, they can play a positive role in mitigating the effects of climate change (Lal, 2016; Mukherjee and Lal, 2013).

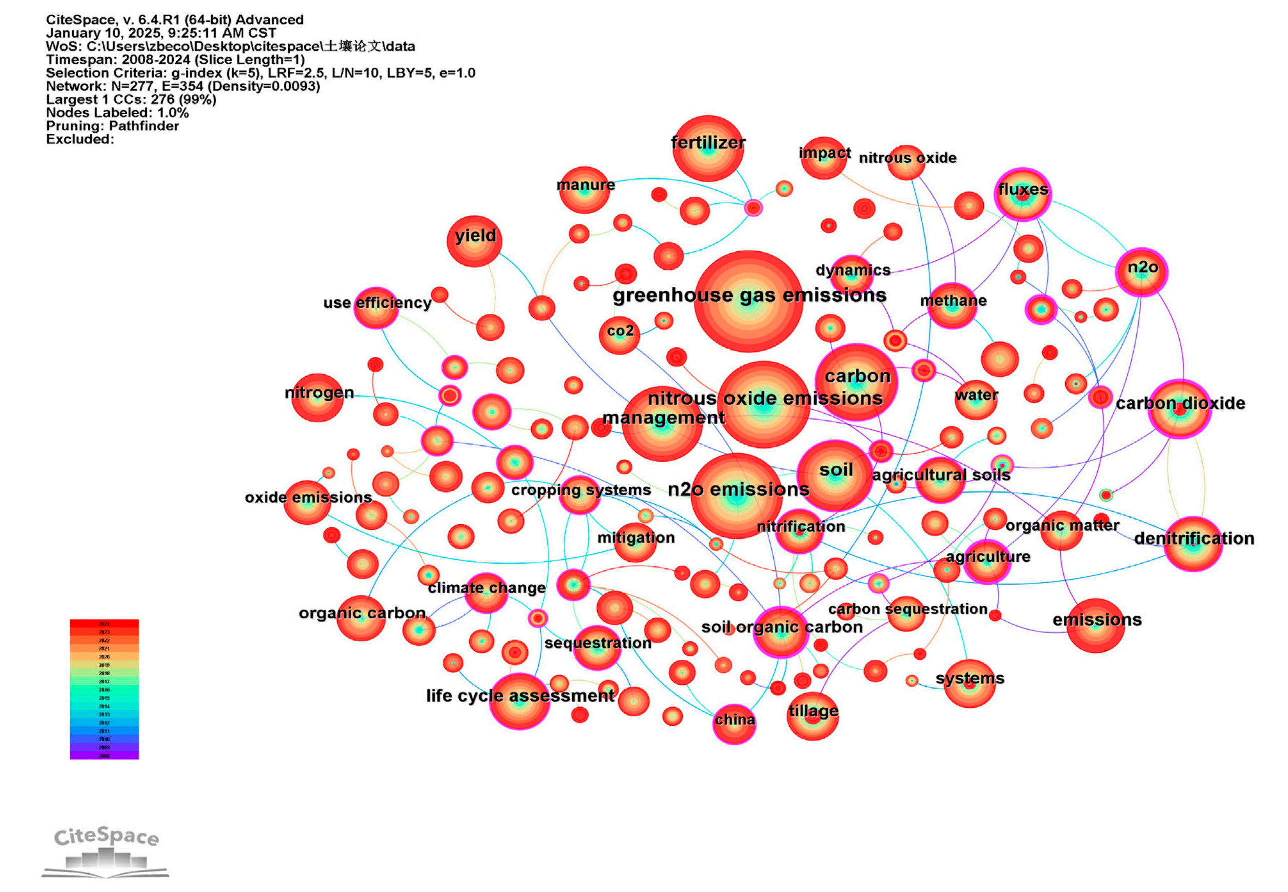

FIGURE 4
Collaboration network map of the keywords co-occurrence.

3.3.3 Literature co-citation analysis

This paper further conducts literature co-citation analysis and summarizes the 10 most cited papers in the field of FCE. As shown in Table 4, the Global meta-analysis of the nonlinear response of soil nitrous oxide (N_2O) emissions to fertilizer nitrogen published in *Proceedings of the National Academy of Sciences* is the article with the most citations since 2008–2024.

Looking at these ten highly cited papers, the research mainly focuses on the relationship between fertilizer application and greenhouse gas emissions, explores the impact of different fertilizers (such as organic fertilizers) on greenhouse gas emissions and carbon benefits, evaluates the agronomic factors of their emissions and the emission factors after the addition of global agricultural soil organic amendments. The greenhouse gases studied mainly include N_2O and carbon dioxide (CO_2) (Shcherbak et al., 2014). These studies are of great significance for understanding the complex impact of fertilizer application on carbon emissions, formulating scientific fertilizer management strategies to reduce greenhouse gas emissions, and achieving sustainable agricultural development.

3.4 Keyword analysis

Keyword analysis is crucial for gaining insights into the core concepts and frontier dynamics of a specific academic field (Seale and Charteris-Black, 2010). Keywords carry crucial information as a highly condensed representation of the content of literature. As emphasized by Kevork and Vrechopoulos (2009), keywords highlight the core themes of the research field, and their frequency of occurrence, centrality, and co-occurrence relationships can all provide a strong basis for judging research hotspots and trends. Based on this, we conduct keyword analysis in FCE, including co-occurrence, clustering, and burst analysis.

3.4.1 Keyword co-occurrence network analysis

Keyword co-occurrence analysis can reveal the frequency of different keywords in a particular field and reflect the associations between research topics. In the keyword co-occurrence map, the larger the node, the higher the frequency and centrality of the keyword, indicating the research hotspots and academic frontiers in this field more clearly. The color around the node represents the year when the keywords co-occur, and the width of the connection represents the strength of the collaborative relationship between the keywords (Cheng et al., 2018; Fan et al., 2024).

In Figure 4, in terms of network density and scale, the number of nodes N = 277, the number of connections E = 354, and the network density = 0.0093. Table 5 further lists the top 10 high-frequency keywords. It can be seen that "greenhouse gas emissions" are the keyword with the highest frequency of occurrence, indicating that it has received extensive attention in this field. Other keywords are

TABLE 5 Top 10 high-frequency keywords on FCE research.

Ranking	Key words	Frequency	Centrality	Year
1	greenhouse gas emissions	660	0.07	2008
2	N_2O emissions	525	0.08	2008
3	nitrous oxide emissions	515	0.12	2008
4	nitrous oxide	410	0.04	2008
5	management	394	0.13	2008
6	carbon	389	0.08	2008
7	soil	371	0.06	2008
8	carbon dioxide	340	0.13	2008
9	fertilizer	306	0.1	2008
10	carbon footprint	234	0.07	2010

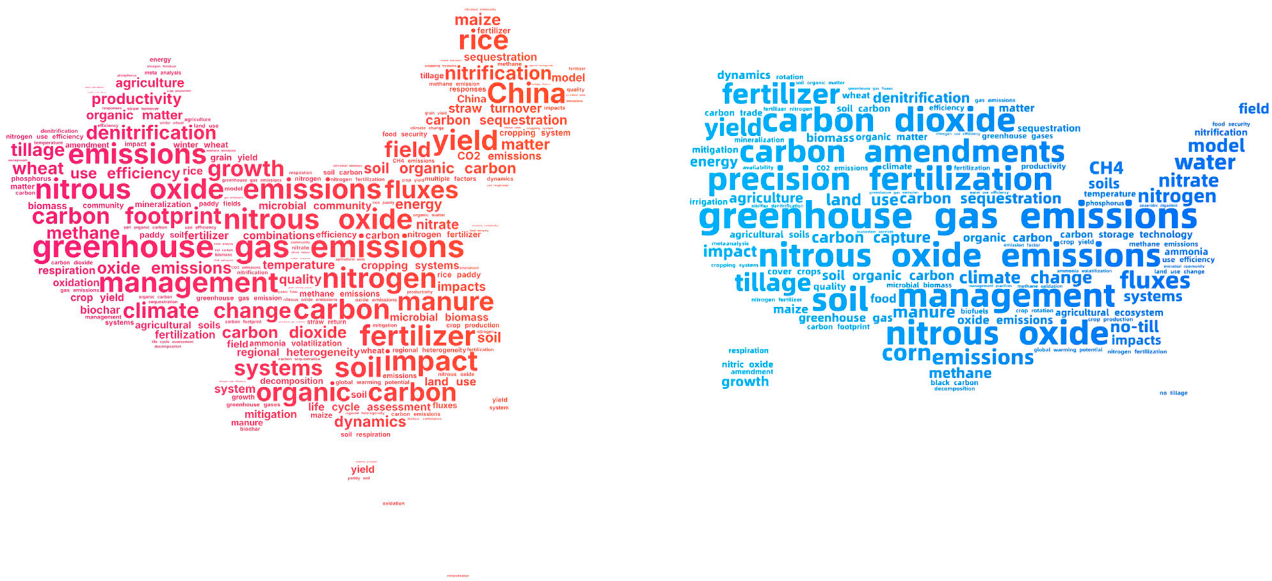

FIGURE 5
Keyword cloud map for FCE in China and the United States.

"N_2O emissions", "nitrous oxide emissions," "management," "carbon," "soil," "carbon dioxide," "fertilizer," and "carbon footprint." This ranking shows that the research focusses in this field in the past have mainly been on the relationship between fertilizer application and greenhouse gas emissions, and through the research on management measures and emission reduction strategies, quantitative assessment methods, and the research and development of new fertilizers and technologies, it aims to explore synergistic pathways to reduce carbon and nitrogen emissions.

In addition, as the two major core entities in global research on FCE, the research themes and approaches of China and the United States in this field hold great reference significance. Given this, this paper extracts the literature published by China and the United States in FCE research, respectively. It accurately extracts keywords from the literature of each country using CiteSpace software. Furthermore, keyword cloud maps are created based on these keywords to visually present the core research themes of the two countries.

For Figure 5, the research topics in the field of FCE in China and the United States show some common characteristics, and they focus on the light of their national conditions. At the level of commonality, China and the U.S. show some research synergy. (1) The integration of Carbon and Nitrogen Emissions. In the keyword cloud map, "nitrous oxide", "methane" and "carbon dioxide" constitute a three-element gas matrix of common concern to the two countries (Zhang et al., 2020; Sistani et al., 2011). Among them, the keyword "nitrous oxide" has the highest frequency, confirming its core position in the research of fertilizer reduction. (2) The quantification of the carbon footprint empowers emission reduction. An assessment framework is constructed around the "carbon footprint," considering many factors such as soil use, fertilizer types, and application rates, and mathematical

TABLE 6 Keyword clustering labeling data sheet on FCE research.

Cluster Number	Cluster name	Cluster Size	Silhouette	Mean Year	Cluster label
#0	N_2O emissions	22	0.957	2014	N_2O emissions; Carbon; Ammonia volatilization; Soil N_2O emissions; Nitrification Inhibitors
#1	Methane emission	21	0.912	2013	Methane emission; Nitrous oxide emissions; N_2O; Rice field; Organic fertilization
#2	Global warming potential	20	0.962	2013	Global warming potential; Soil organic Carbon; Dynamics; Residues; Quality
#3	Nitrous oxide	20	0.932	2013	Nitrous oxide; Denitrification; Nitrification inhibitor; Greenhouse gas emission; Nitrate
#4	Carbon sequestration	20	0.912	2014	Carbon sequestration; Soil organic matter; Fertilizer; Denitrifiers; Microbial community
#5	GHG emissions	20	0.958	2014	GHG emissions; Biochar; Dioxide; Agricultural carbon emissions; Pyrolysis temperature
#6	Carbon dioxide	19	1	2013	Carbon dioxide; Fluxes; Carbon footprint; Emission factor; Nitric oxide
#7	Respiration	19	0.885	2014	Respiration; Microbial biomass; Phosphorus; Carbon dioxide emission; Nitrogen fertilizer
#8	Life cycle assessment	18	0.89	2015	Life cycle assessment; Greenhouse gas; Carbon emission; Carbon dioxide; N_2O emissions
#9	Carbon footprint	18	0.918	2014	Carbon footprint; Greenhouse gas emission; Crop production; Life cycle assessment; Carbon dioxide
#10	Greenhouse gas emission	16	0.892	2010	Greenhouse gas emissions; N_2O emission; Life-Cycle analysis; Sustainable intensification; Greenhouse gases
#11	Organic fertilizer	16	0.87	2017	Organic fertilizer; Soil respiration; Economic benefit; Nitrous oxide; Chemical fertilizer
#12	Nitrogen fertilizer	15	0.975	2016	Nitrogen fertilizer; Methane emissions; Ammonia emissions; Reactive n losses; Meta-analysis
#13	Climate change	14	0.88	2011	Climate change; Greenhouse gases; Soil carbon; Land use; Global warming
#14	Impacts	13	1	2014	Impacts; Matter; Net ecosystem Carbon budget; Nitrous oxide; Straw return
#15	Rice yield	8	0.938	2020	Rice yield; NH_3 Volatilization; Straw incorporation; Net ecosystem Carbon budget; NH_3 emission
#16	Carbon emissions	7	0.95	2021	Carbon emissions; CO_2 emissions; Chemical fertilizer use; Economic growth; Energy consumption
#17	Agricultural soil	7	0.914	2012	Agricultural soils; Urease; Climate change; Microbial community; Enzyme activity

model is carefully designed to provide accurate data support for agricultural carbon emission reduction decisions (Jaiswal and Agrawal, 2020; Li M. et al., 2020).

Rooted in the profound differences in the agricultural ecology and policy objectives between China and the United States, there is also a certain degree of research heterogeneity in FCE. On the one hand, for China, a large country with a large population, ensuring food security is a top priority. Therefore, “rice” and “wheat” are attracting considerable attention in the word cloud (Song et al., 2024; Liu et al., 2024). Meanwhile, the vast area of China, spanning from the eastern monsoon zone to the northwestern arid zone, exhibits significant differences in soil and climate conditions, which quickly lead to distinct fertilizer responses and carbon emission patterns. Therefore, studying “regional heterogeneity” is indispensable (Cui et al., 2022). Additionally, China’s agricultural production is substantial, and the production of straw is considerable. Straw turnover has attracted much attention. Reasonable turnover can reduce incineration pollution, increase soil organic matter, sequester carbon, and enhance production, which aligns with sustainable development under limited resources (Bai et al., 2023; Guo et al., 2024).

On the other hand, keywords such as “precision fertilization,” “carbon capture,” and “carbon storage technology” are prominent in the American word cloud, which is in line with the concept of sustainable development under limited resources. “carbon capture” and “carbon storage technology” stand out in the keywords, closely related to its current agricultural development and advantages. Agricultural production in the United States is highly mechanized and scaled, so precision fertilization technology is widely used Evett et al. (2020). Shah and Wu (2019) showed that precision fertilization not only ensures improve crop yields but also

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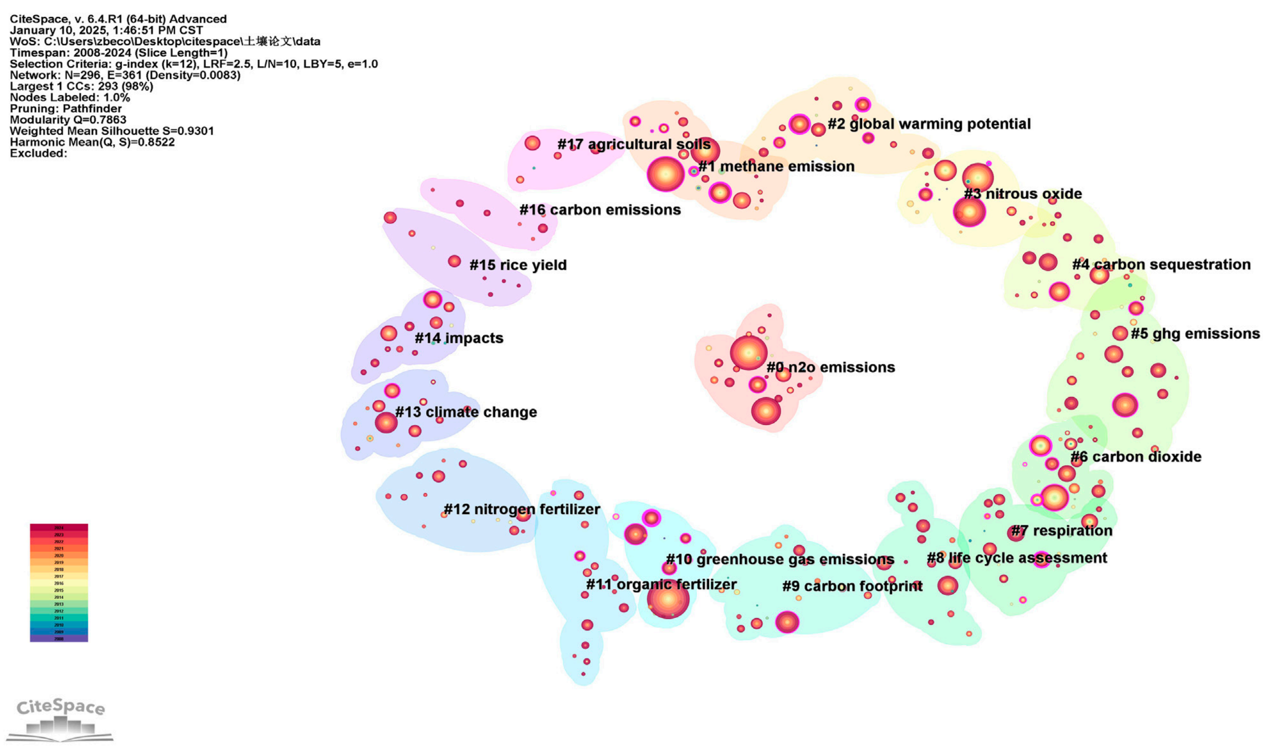

FIGURE 6
Cluster map of keywords on FCE research.

effectively inhibits the waste of fertilizer. Meanwhile, the United States is exploring "carbon capture" and "carbon storage technology" based on its own financial resources and scientific research foundation (Van Alphen et al., 2010). The technology of capturing carbon dioxide and injecting it into the ground reflects the United States' strategy to strengthen technological breakthroughs in the field of fertilizer emission reduction (Qiu and Yang, 2018; Lau et al., 2021).

3.4.2 Keyword clustering analysis

Clustering analysis can accurately present the main research segments of the field (Wang and Lu, 2020). The research hotspots in FCE can be determined by forming a keyword clustering map and a timeline map. This paper uses CiteSpace to conduct clustering analysis, sets the period from 2008 to 2024, the time slice as "1", selects "keyword" as the node type, and uses the Log-Likelihood Ratio (LLR) method to cluster the keyword co-occurrence map, forming a total of 18 clusters. The modularity value of the clusters Q = 0.7863 > 0.3, indicating a significant clustering structure. The average silhouette value S = 0.9301 > 0.7, indicating that the clustering results are convincing. To present the keyword clustering more clearly, this study also created a table showing the number of labels, silhouette values, and average years for the 18 clusters. Each cluster comprises multiple closely related keywords, arranged in order from #0 to #17, and smaller numbers represent clusters containing more keywords.

By integrating the keyword clustering table related to FCE (Table 6), the cluster co-occurrence map (Figure 6), and the timeline map (Figure 7), this paper further summarizes and analyzes the research hotspots from 2008 to 2024 and finds that the research focuses on three themes:

First, the correlation mechanism between different types of fertilizers and carbon emissions. Nitrogen fertilizer (#12) occupies an important position in early research in the field of fertilizer carbon emission. As a widely used fertilizer type in agricultural production, the production process of nitrogen fertilizer consumes a large amount of energy, leading to increased CO_2 emissions (Menegat et al., 2022). Meanwhile, N_2O emissions (#0) are caused by a series of biochemical reactions after nitrogen fertilizers are applied to the soil, exacerbating climate change (#13) (Signor et al., 2013). The research hotpots focus on the differences in carbon emissions of different nitrogen fertilizer types under different conditions. With the deepening of the research, organic fertilizers (#11), a type of green fertilizer, have gradually come into the research scope. Applying organic fertilizers has a dual impact on carbon emissions. For one thing, Organic fertilizers can increase the soil's organic carbon content and improve the soil carbon sequestration capacity (#4) (Gonçalves et al., 2023). For another, methane (#1) may be generated during the decomposition process of organic fertilizers (Signor et al., 2013). The hotpots focus on the specific influence mechanism of the type of organic fertilizer on carbon emission, aiming to find a reasonable application strategy of organic fertilizer that can both improve soil fertility and reduce carbon emission.

Second, the impact of fertilizers on soil carbon cycling and carbon emissions. Agricultural soils (#17) are important sites for

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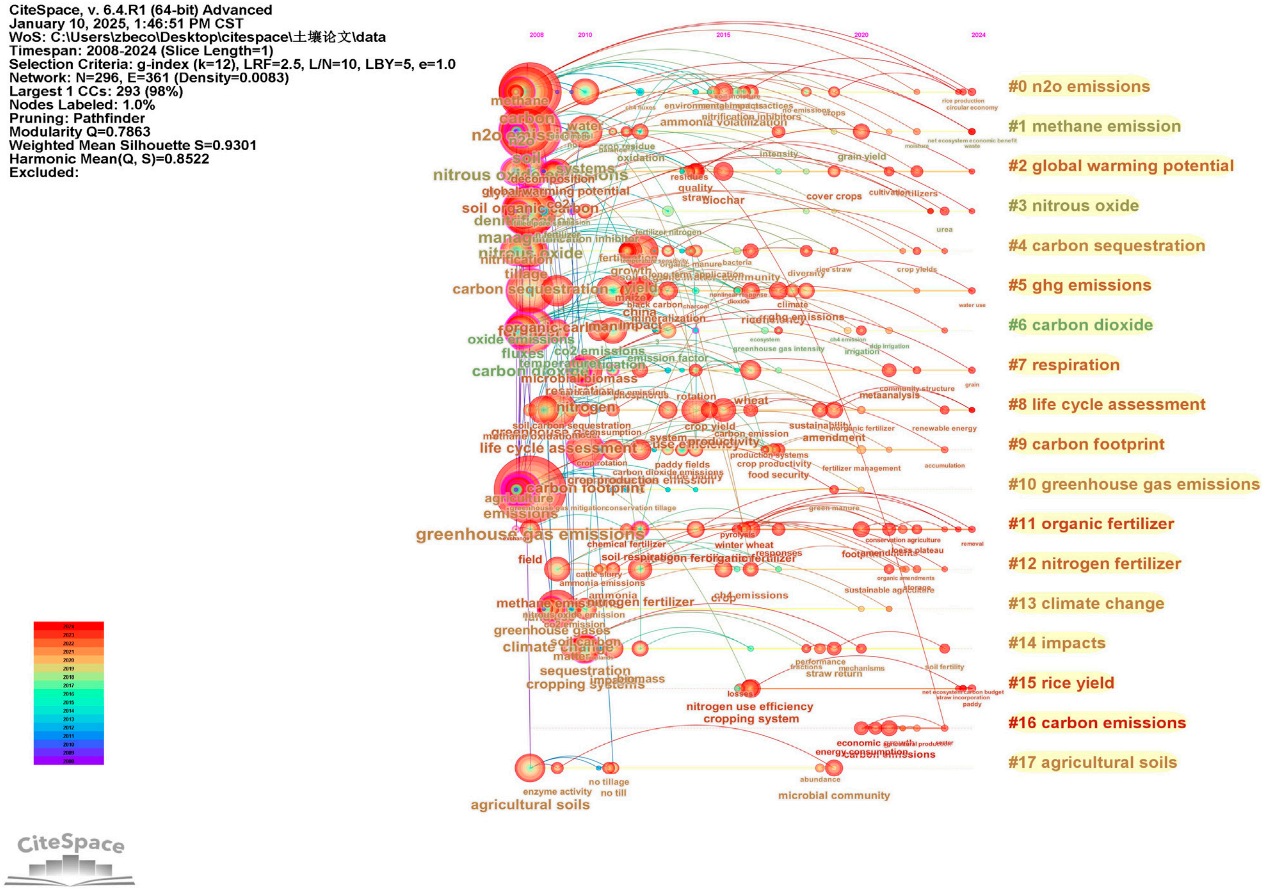

FIGURE 7
Keyword clustering timeline diagram on FCE research.

carbon storage and carbon emissions. The application of fertilizers can have a profound impact on the soil carbon cycle process, which in turn affects carbon emissions (#16). The related research spans the entire period. Early research has found that fertilizers can alter the structure and activity of the soil microbial community, and microorganisms play a crucial role in the decomposition and transformation of soil carbon (Gonçalves et al., 2023; Yuan et al., 2018).

On the one hand, certain fertilizers can promote the growth of microorganisms that decompose organic carbon in the soil and accelerate the decomposition of soil organic carbon (Wang et al., 2023b); on the other hand, some fertilizers are conducive to the formation of stable soil aggregates, which wrap organic carbon in them and reduce the decomposition of organic carbon (Zhao et al., 2023).

Since 2012, research on the relationship between fertilization factors and soil carbon emissions has gradually increased. Premature fertilization time may lead to too long biochemical reaction time of fertilizer in the soil, increasing the risk of carbon emissions (Tyagi et al., 2022); the method of deep fertilizer application can improve the utilization rate of fertilizer and reduce carbon emissions by affecting soil respiration and other related processes (#7) (Chen et al., 2020).

Finally, the comprehensive assessment of FCE. The Life Cycle Assessment (#8) method has been widely used in the research on FCE to comprehensively assess the carbon emissions throughout the entire life cycle of fertilizers, including raw material extraction, production, transportation, application, and waste treatment. Through this comprehensive assessment, the key links and hotspots of FCE can be identified, which is helpful for accurately calculating the carbon footprint (#9) and providing a basis for formulating targeted emission reduction strategies (Thies et al., 2020). In addition, from the perspective of system science, the recent study focuses on the synergistic optimization of crop yield (#15) and greenhouse gas emissions (#10) (Gaihre et al., 2023), and is committed to exploring the effective control of carbon emissions under the premise of ensuring food security, which will help to achieve the goal of reducing agricultural emissions and stabilizing yields, and lay a scientific foundation for a green and low-carbon transition in global agriculture.

3.4.3 Keyword burst analysis

Keyword burst refers to tracking the sudden increase in the frequency of use of certain keywords within a specific period. Suppose certain keywords in the research field suddenly emerge significantly quickly. In that case, it indicates a surge in the research on specific topics in this field during that period, which can be used

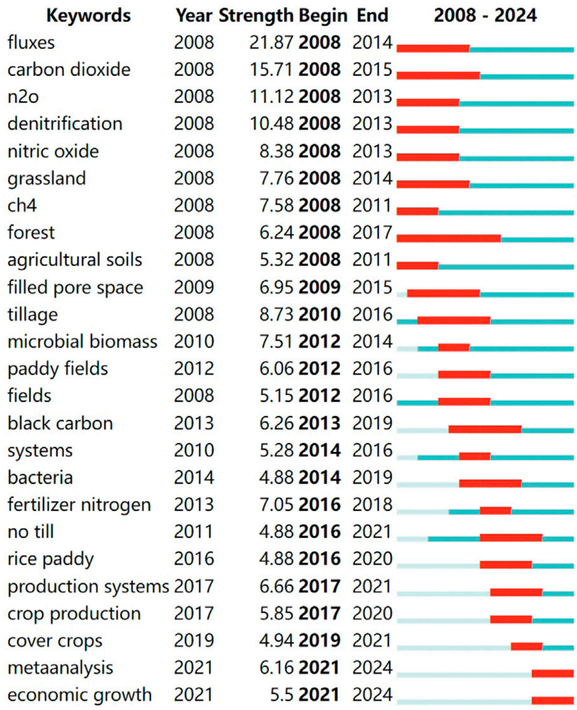

FIGURE 8
Top 25 keywords with the strongest citation bursts on FCE.

to identify the research hotspots in different years. Figure 8 shows the top 25 keywords with the most vigorous burst intensity in FCE from 2008 to 2024. From the perspective of fertilizer types, "fertilizer nitrogen" increased significantly in this period, which aligns with the clustering analysis and reinforces the notion that the production, transportation, and application processes of nitrogen fertilizers are closely tied to carbon emissions, as they are a commonly used type in agricultural production.

From the perspective of fertilizer application, "tillage" burst from 2008 to 2016, and "no-till" burst from 2011 to 2021. The tillage method is closely related to fertilizer application and carbon emissions. Traditional tillage methods may damage the soil structure, increase the contact between the soil and the air, and thus accelerate the decomposition of soil organic carbon and carbon emissions (Ning et al., 2024). In contrast, no-till can reduce soil disturbance, help maintain the soil's organic carbon content and may also change the distribution and transformation processes of fertilizers in the soil, affecting carbon emissions (Lee et al., 2024).

From the perspective of the role of fertilizers in the soil, "agricultural soil" burst from 2008 to 2011, indicating that as an important place for fertilizers to play their role, after fertilizers are applied to the soil, they will interact with the physical, chemical, and biological processes in the soil, and thus affect carbon emissions (Edmeades, 2003; Thies et al., 2020). This essential element received attention in the early research stage on FCE and echoes the clustering analysis.

Another, "filled pore space" burst from 2009 to 2015, highlighting the importance of the factor of soil pore structure. The soil pore space affects the air permeability and moisture conditions of the soil, which are closely related to the activity of soil microorganisms. "Microbial biomass" burst from 2010 to 2014 and plays a key role in fertilizer transformation and carbon emissions. Microorganisms are an essential part of the soil ecosystem, and they actively participate in fertilizers' decomposition, transformation, and nutrient cycling processes. Different fertilizers will affect the community structure and biomass of soil microorganisms and thus influence the transformation pathways of carbon and nitrogen in the soil and the situation of greenhouse gas emissions (Bilandžija et al., 2016). These two burst keywords further supplement and demonstrate the second theme of the clustering analysis: the impact of fertilizers on soil carbon cycling and carbon emissions, helping to better understand the research hotspots in the field of FCE in recent years.

4 Discussion

4.1 Research themes and gaps

Research on FCE has gained significant traction over the past decade, forming a dynamic field at the intersection of agricultural science, environmental studies, and climate change mitigation. A review of recent bibliometric literature shows that three main research themes dominate the FCE domain. To begin with, a large body of work focuses on quantifying emissions, particularly N_2O, from fertilizer application using empirical and model-based methods. This includes assessments of fertilizer types, production processes, and usage intensity (Zheng et al., 2024; Ren et al., 2025).

In addition, scholars have increasingly explored the biological and soil ecological mechanisms underpinning fertilizer, which can alter the structure and activity of the soil microbial community, and microorganisms play a crucial role in the decomposition and transformation of soil carbon, thereby influencing both carbon retention and greenhouse gas release (Yuan et al., 2018). Finally, the balance between carbon sequestration and N_2O emissions has gradually attracted attention. Some fertilizers and soil amendments can promote carbon storage by increasing organic matter inputs, they may simultaneously stimulate microbial processes, which elevate N_2O emissions (Signor et al., 2013; Gonçalves et al., 2023).

This study confirms several of these existing findings. Similar to Ren et al. (2025), our co-citation and keyword analyses identify "greenhouse gas emissions", "N_2O emissions", "carbon footprint", and "biochar" as the most persistent research hotspots. These are consistent with the dominant concerns in sustainable fertilizer management and agricultural GHG mitigation. The temporal staging of FCE research identified in this study mirrors prior attempts to segment research trajectories based on bibliometric inflection points (Wu et al., 2024; Hu et al., 2024). Moreover, both our findings and those of Gao et al. (2024) confirm a recent surge in interest around lifecycle assessment, slow/controlled-release fertilizers, and emission reductions through innovative soil management strategies.

Based on the bibliometric results, two underexplored research gaps emerge within the FCE literature. First, while the balance between carbon sequestration and N_2O emissions is receiving growing attention, related studies remain fragmented and lack a systematic framework. More integrated research is needed to understand how fertilizer practices affect both processes and to guide strategies that maximize co-benefits. Second, while existing studies confirm that interactions between soil properties and microbial communities are influenced by fertilizer inputs, few have specifically examined how different types of fertilizers alter these soil–microbe dynamics. Although emerging topics like "filled pore space" and "microbial biomass" indicate growing interest in this area, most research remains descriptive and lacks differentiation by fertilizer type.

4.2 Contributions

This study extends existing literature in two significant directions:

Firstly, we move beyond static keyword co-occurrence by integrating timeline visualization, clustering analysis, and burst detection to reveal the dynamic evolution of FCE research. This integrated approach not only identifies long-standing thematic clusters, such as "N2O emissions", "carbon sequestration", but also reveals short-term bursts in attention to emerging topics like "filled pore space" and "microbial biomass", which highlight new directions in soil–microbe–fertilizer interactions. Through temporal mapping and structural clustering, we are able to trace how research priorities have shifted: from early concerns with nitrogen-related emissions toward more holistic, system-based topics such as fertilizer synergies, organic amendments, and soil health, which helps pinpoint underexplored gaps and emerging frontiers in the FCE literature.

Secondly, we contribute a cross-national comparative perspective by analyzing keyword cloud maps of publications from China and the United States. While prior studies acknowledge that both countries lead in publication volume (Bilandžija et al., 2016; Yang et al., 2023), few have examined their thematic divergence. Our results reveal that Chinese research tends to prioritize staple crop systems and regional agroecological variability, reflecting concerns around food security and land sustainability. In contrast, U.S. research emphasizes high-tech strategies such as "precision fertilization", "carbon capture", and "storage technologies", aligned with resource-intensive agricultural practices. This comparative lens not only highlights national differences in research orientation but also underscores the need for differentiated policy and technological pathways in addressing emissions related to fertilizer use.

4.3 Future research suggestions

Future research should adopt more integrative frameworks. First, studies should investigate the dual impacts of fertilizers on carbon sequestration and N_2O emissions through integrated empirical approaches that simultaneously measure both outcomes across diverse fertilizer regimes. This requires long-term field trials and modeling efforts that explicitly quantify trade-offs and co-benefits in different agroecosystems. Second, priority should be given to elucidating how specific fertilizer types modulate soil-microbial interactions. Advanced research techniques could provide functional mechanistic insights into microbial community responses to fertilizer-induced changes in soil properties. Finally, given the distinct regional priorities observed between China and the United States, cross-national comparative studies should be encouraged to develop context-specific solutions and inform differentiated policy strategies for sustainable fertilizer management.

5 Conclusions and challenges

5.1 Conclusions

This paper uses CiteSpace software to conduct knowledge mapping and bibliometric analysis of 2,494 literatures in the field of FCE included in the WOS database from 2008 to 2024 and draws the following conclusions:

(1) Regarding the timing and number of publications, research in the field of FCE has shown an exponential upward trend in the past two decades, divided into three stages: initial exploration in 2008–2011, steady development in 2011–2019, and rapid growth after 2019. The research focus is gradually focusing on carbon emission mechanisms, carbon balance and green benefits of fertilizers.

(2) From the perspective of the pattern of research forces, 109 countries have participated in the construction of the extensive scientific research network. China and the United States lead in the number of publications, and the

research topics are both common and unique. However, the author collaboration ecosystem is not perfect, with a high proportion of independent scholars, and cross-institutional, cross-disciplinary, and cross-team cooperation needs to be strengthened, which limits knowledge interaction and the emergence of innovative inspiration.

(3) According to the co-cited analysis, *Rattan Lal* is the most cited author in the field, and *Agriculture, Ecosystems & Environment* is the most influential journal. Highly cited papers focus on the link between fertilizers and greenhouse gas emissions, which is important for achieving the Sustainable Development Goals in agriculture.

(4) Keyword analysis shows that greenhouse gas emissions are a research hotspot. Cluster analysis sorts out three major themes: fertilizer type, soil carbon cycle and comprehensive assessment. Emergent analysis explores the phased fluctuations of FCE research hotspots from three aspects: fertilizer type, tillage method and agricultural soil, echoing each other with cluster analysis, jointly demonstrating the dynamic evolution and frontier trends of the research field, providing strong support for understanding the academic *status quo* in this field.

5.2 Challenges

Although this study provides a comprehensive bibliometric analysis of FCE research from 2008 to 2024, it still has several limitations. First, the data source is limited to the Web of Science Core Collection and includes only English-language publications. This may lead to the omission of relevant studies published in other databases or languages, such as Chinese, which could be significant given China's large research output in this field. Second, the bibliometric approach focuses on structural and quantitative features of the literature, such as co-citation and keyword frequency, but cannot capture the full depth of theoretical insights, methodological quality, or contextual nuances of individual studies.

Beyond these methodological constraints, the FCE research field itself exhibits several structural challenges. One major issue is the lack of unified accounting standards for fertilizer-related carbon emissions, which hampers data comparability and cross-regional synthesis. Additionally, much of the existing literature is regionally focused and crop-specific, leading to fragmented insights with limited generalizability. Finally, interdisciplinary integration across agronomy, environmental science, and climate policy remains insufficient, restricting the development of holistic, system-based approaches to emission mitigation.

To advance the field, future research should broaden data sources, incorporate qualitative synthesis, work toward harmonizing carbon accounting standards and promote interdisciplinary collaboration to enhance the theoretical, methodological, and practical depth of FCE studies.

Author contributions

LY: Writing – original draft, Funding acquisition, Project administration. ZW: Writing – original draft. YC: Writing – review and editing. YS: Supervision, Writing – review and editing. LZ: Methodology, Writing – review and editing. WW: Methodology, Writing – review and editing. XZ: Software, Writing – review and editing. ZL: Funding acquisition, Project administration, Writing – review and editing. GW: Conceptualization, Writing – review and editing.

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Conflict of interest

Authors YS, LZ, WW, and XZ were employed by Stanley Agricultural Group Co. Ltd.

The remaining 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.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

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