agriculture

Review

The Role of Fertilization on Soil Carbon Sequestration in Bibliometric Analysis

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Abstract: The soil carbon pool is the largest and most dynamic carbon reservoir in terrestrial ecosystems. Fertilization, an important component of agricultural management, is a significant factor influencing soil carbon sequestration. This study analyzed literature from the Web of Science from 2008 to 2024 using CiteSpace. The results revealed a steady increase in publications on this topic, with a significant surge in the recent four years. The analysis highlighted key collaborations among countries, institutions, and authors, and identified main journal sources and seminal works in the research on the role of fertilization in soil carbon sequestrations. Keyword analysis indicated that current research hotspots include 'soil organic carbon dynamics and organic matter decomposition', 'microbial community dynamics and carbon cycling', and 'agricultural management practices on carbon sequestration'. In the context of climate change, future research is likely to focus on enhancing sustainable agricultural practices, promoting biochar and resource utilization, and utilizing microbial communities to optimize soil carbon sequestration. This study provides a comprehensive overview of the role of fertilization in soil carbon sequestration, providing important insights for improving soil carbon sequestration strategies.

Keywords: bibliometrics; fertilization; carbon sequestration; CiteSpace; soil microorganisms

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1. Introduction

Soils represent the largest reservoir of carbon [1]. Even small changes in soil organic carbon (SOC) can have a significant impact on atmospheric carbon dioxide levels, thereby influencing climate change [2]. Soil carbon sequestration focuses on stabilizing carbon in long-lived pools in soils, effectively capturing atmospheric CO_2 and storing it in stable forms. This process is beneficial for reducing greenhouse gas emissions and mitigating climate change, as well as ensuring crop production and food security [3,4]. Agricultural soil has great potential for carbon sequestration, as approximately 35 million km^2 of natural vegetation, such as forests, woodlands, and grasslands, representing about 10% of the total land area, have been converted to croplands [5,6]. Therefore, improving SOC content and increasing carbon fixation in agricultural soils are important strategies for combating climate change and promoting sustainable agricultural development [6,7].

Carbon sequestration plays an important role in sustaining and enhancing SOC, which is essential for improving soil quality. Carbon sequestration occurs mainly through the formation and stabilization of soil aggregates, deep SOC fixation, and microbial decomposition and transformation processes [8]. The process of soil carbon sequestration is influenced by various factors, including climate, soil properties, and tillage practices. Among these, fertilization, as a main agriculture management strategy to achieve high crop yield, is important for promoting soil carbon storage [9]. Organic fertilization, in particular, has the potential to increase the total soil carbon content by over 30% [10,11]. The combined use of organic and chemical fertilizer is more effective in enhancing carbon sequestration compared to chemical fertilizers alone [12,13]. Fertilization also alters the soil environment for microorganisms, resulting in changes in microbial community structure and diversity, which in turn affect the turnover and stability of SOC [14,15]. The application of organic fertilizer significantly increases the relative abundance of fungal communities in small macro-aggregates, promoting the production of extracellular polysaccharides that enhance soil aggregation and structure, thereby improving carbon sequestration [16]. Moreover, nitrogen addition increases soil nitrogen availability, accelerating microbial nutrient decomposition and contributing to the formation of stable soil organic matter [17]. Overall, the impact of different fertilization practices on SOC sequestration is complex, requiring multidisciplinary approaches from environmental science, agriculture and ecology. However, a comprehensive quantitative analysis of these effects is needed.

Bibliometrics is an effective method for assessing the status and development of the research field through the analysis of published literature [18]. By employing mathematical statistics and visualization techniques, this method provides insights into the research landscape, including historical trends, current status, key developments, and future directions [19,20]. CiteSpace, a widely utilized bibliometric software, facilitates the analysis of countries, institutions, journals, and authors. It also highlights key research topics through network analysis and clustering algorithms [21]. This approach has been applied successfully in various fields, such as plant rhizosphere microorganisms [22], resistance genes in organic solid waste compost [23], and ecological restoration [24]. Given the complexity of the impact of fertilization on SOC content and sequestration capacity, bibliometric analysis can shed light on the research trends in this field and identify potential directions for future study.

Using the bibliometric function of CiteSpace, this study analyzed literature from recent years related to the effects of fertilization on soil carbon sequestration, sourced from the Web of Science (WOS). Our study aimed to identify research hotspots and emerging trends in this field. Specifically, this study addresses the following objectives: (1) outlining the basic characteristics of the literature and identifying major research contributors and collaborations; (2) summarizing the primary research topics and hotspots; and (3) predicting future research directions. This analysis provides valuable insights that can inform and guide subsequent research in this field.

2. Materials and Methods

2.1. Data Collection

The literature search was conducted using the Web of Science (WOS) Core Collection, a comprehensive database that includes tens of thousands of influential academic journals and serves as an important resource for scientific research [25]. We employed the "Advanced search" feature of the WOS Core Collection, and we used TS = ("fertiliz*") AND TS = ("*carbon sequestration" OR "*carbon fixation" OR "*carbon storage") AND TS = ("soil"). The search was conducted on 1 July 2024. We limited the results to "Article" and "Review Article" published between 2008 and 2024. The retrieved records were exported in the "Full Record and Cited References" format as a plain text file for subsequent bibliometric analysis. The results were imported into CiteSpace, where duplicate articles were eliminated using its deduplication feature. In total, 2347 publications were identified for analysis. The search and analysis process is shown in Figure 1.

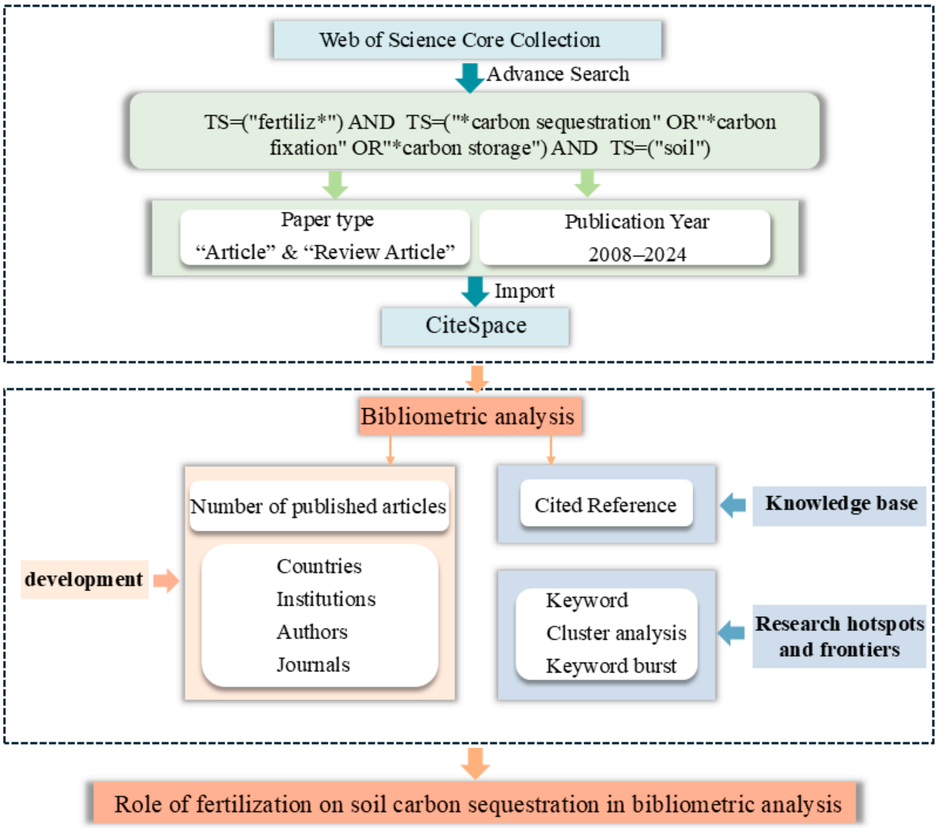


Figure 1. Research workflow chart.

2.2. Analytical Method

In this study, we used version 6.3.R1 of CiteSpace, a powerful tool for bibliometric analysis, to visualize and analyze the WOS literature search results [26]. Firstly, we analyzed the number of publications and their growth rate using the de-duplicated data. Afterwards, we performed a co-occurrence analysis to examine the role of fertilization in soil carbon sequestration, focusing on key nodes such as country, institution, author, journal and significant literature, to understand the current status of research in this field. Furthermore, we performed a keyword clustering analysis to identify research trends and hotspots, followed by a keyword burst analysis to explore emerging research directions. Based on these analyses, we provide a summary of the current research landscape and offer insights into potential future research directions.

3. Results and Discussion

3.1. Publication Analysis

A total of 2918 publications on the role of fertilization in soil carbon sequestration, published between 1 January 2008 and 1 July 2024, were analyzed in this study. Overall, the number of articles showed an upward trend over time. The research can be broadly divided into three stages: the initial period, the development period, and the booming period (Figure 2). During the initial period (2008–2013), articles accounted for 16.62% of the total output, with approximately 80 papers published per year. Although the research on soil carbon sequestration in croplands was limited during this stage, it established a theoretical foundation for future studies on fertilization management strategies for enhancing soil carbon sequestration [27,28].

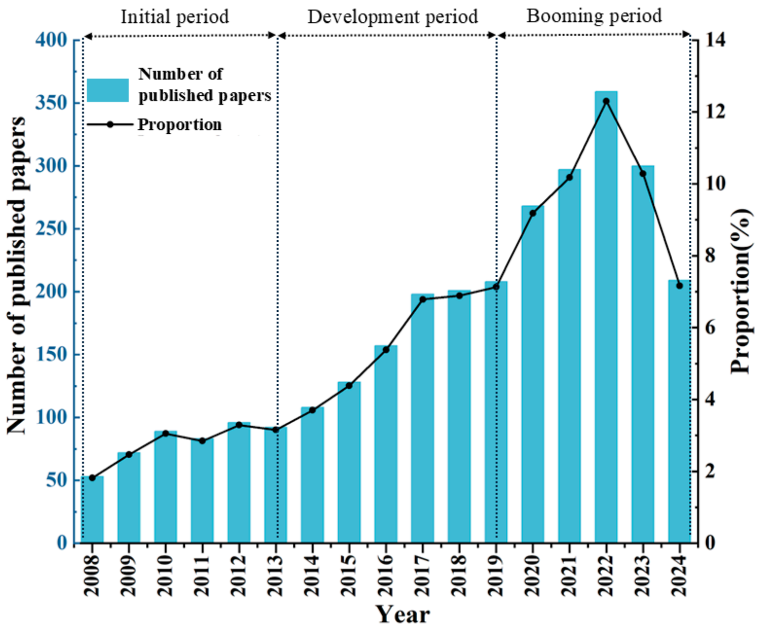


Figure 2. Annual literature output and proportion on the role of fertilization on soil carbon sequestration during 2008–2024. The proportion was calculated by dividing the annual number of publications by the total number of publications from 2008–2024.

During the development period (2014–2019), there was a substantial increase in the number of publications, which accounted for 34.27% of the total number of publications by the end of 2019. This increase was closely linked to the growing global recognition of the critical role of soil in carbon sequestration. For example, the launch of the Global Soil Partnership by the Food and Agriculture Organization of the United Nations (FAO) in 2012 promoted global research on soil health and carbon sequestration. Additionally, the signing of the Paris Agreement in 2015 further emphasized the potential of soil as a carbon sink. These international dynamics have encouraged numerous international researchers to focus on the role of microorganisms in the accumulation and transformation of SOC under different fertilization practices [29,30].

Since 2020, the field has entered the "booming period" of development. From 2020 to 2024, the number of published papers increased significantly, reaching its peak in 2022. During this period, 50% of all articles in the field were published. This surge in research output was influenced by various policies and international initiatives, such as China's "carbon peaking and carbon neutrality" in 2020 and the European Union's latest Common Agricultural Policy in 2021, which contributed to increased attention on fertilization practices for carbon sequestration. As research in this area continues to advance, it is likely to rapidly progress in response to evolving policy frameworks. The number of publications for 2024 is limited due to the data collection period concluding on 1 July.

3.2. Collaboration Analysis

3.2.1. Analysis of the Contribution of Countries and Institutions

The collaboration among countries and institutions highlights the social relationships and the extent of connections within the field [20]. According to the analysis, research on the impact of fertilization on soil carbon sequestration involved researchers from 118 countries. The top 10 countries with the highest number of publications are shown in Table 1. China led 1120 publications, accounting for 35.05% of the total, followed by the USA with 730 papers, representing 22.85%. Other countries in the top 10 included Germany, India, Australia, Canada, England, Italy, France, and Sweden, each with publication counts between 100 and 200. Additionally, the centrality of China, the USA and Canda was notably higher compared to other countries, indicating their significant academic influence and vital roles in promoting collaboration within the field.

Table 1. Top 10 countries by number of published papers on fertilization management to improve soil carbon sequestration capacity.

Rank	Country	Counts	Centrality	Proportions (%)	Agricultural Output (2008–2019) ($ trillion)
1	China	1120	0.16	35.05	11.19
2	USA	730	0.15	22.85	4.22
3	Germany	261	0.07	8.17	0.62
4	India	252	0.03	7.89	4.53
5	Australia	180	0.03	5.63	0.48
6	Canada	160	0.12	5.01	0.54
7	UK	132	0.08	4.13	0.34
8	Italy	131	0.05	4.10	0.49
9	France	129	0.07	4.40	0.72
10	Sweden	100	0.03	3.13	0.05

A total of 457 institutions from different countries contributed to research on the role of fertilization on soil carbon sequestration. Of these, 54 published more than 20 papers (Table 2). The Chinese Academy of Sciences led with 53 publications, followed by the Ministry of Agriculture & Rural Affairs (195 counts), Chinese Academy of Agricultural Science (152 counts), Indian Council of Agricultural Research (ICAR) (150 counts), United States Department of Agriculture (USDA) (121 counts), and Northwest A&F University China (120 counts). Notably, seven of the top 10 institutions were from China, highlighting the country's significant influence in this field. Ranked second, the USA had one institution in the top 10 and was the first to publish relevant papers, pioneering the exploration of the role of fertilization in soil carbon sequestration (Figure 3). In contrast, Chinese institutions showed a rapid increase in publications in recent years, with outputs growing annually.

Table 2. The top 10 research institutions in terms of number of published papers on fertilization management to improve soil carbon sequestration capacity.

Rank	Institution	Counts	Centrality
1	Chinese Academy of Science	532	0.39
2	Ministry of Agriculture & Rural Affairs	195	0.26
3	Chinese Academy of Agricultural Science	152	0.20
4	Indian Council of Agricultural Research (ICAR)	150	0.18
5	United States Department of Agriculture (USDA)	121	0.10
6	Northwest A&F University China	120	0.14
7	Institute of Agricultural Resources & Regional Planning	95	0.14
8	Nanjing Agricultural University	88	0.23
9	Nanjing Institute of Soil Science	84	0.26
10	INRAE	81	0.14

Moreover, according to Our World in Data, countries with a high publication output, such as China and the United States, also lead in agricultural productivity (Figure 4) [31]. The strong correlation between high agricultural output and significant publication volumes in these countries is largely linked to national policies focused on sustainable agriculture and environmental protection. For instance, China's Farmland Quality Protection promotes measures such as optimizing fertilization strategies and replacing chemical fertilizers with organic alternatives to improve soil health and enhance agricultural carbon sequestration. Similarly, the U.S. Department of Agriculture's Conservation Reserve Program and other sustainable agriculture initiatives, as well as Europe's Common Agricultural Policy, have contributed to improved soil management practices aimed at mitigating climate change. The correlation between publication output, agricultural productivity, and policy underscores the need for a closer collaboration between agriculture and scientific research. In conclusion, strengthening international collaboration and policy support is crucial for advancing progress in this important field.

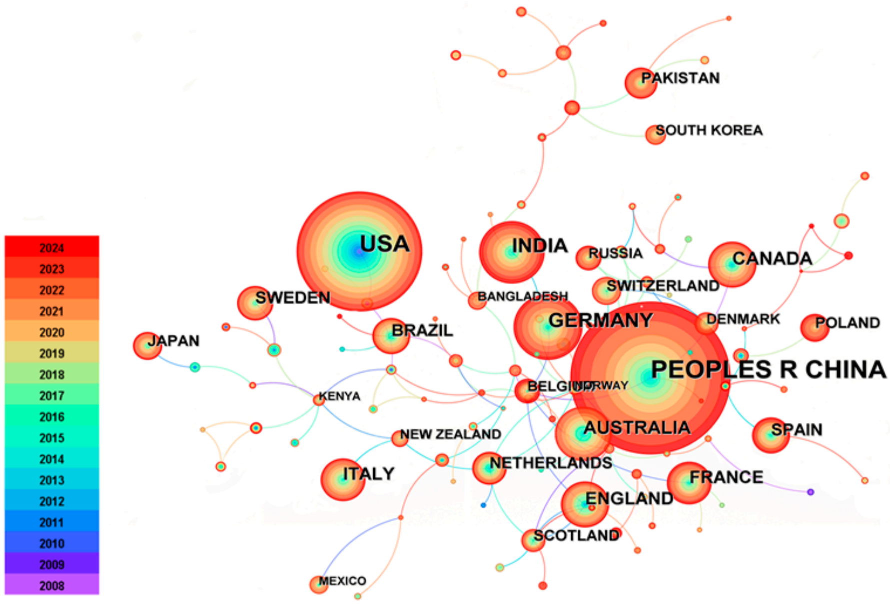


Figure 3. Countries' research cooperation networks in the field of fertilization's role on soil carbon sequestration.

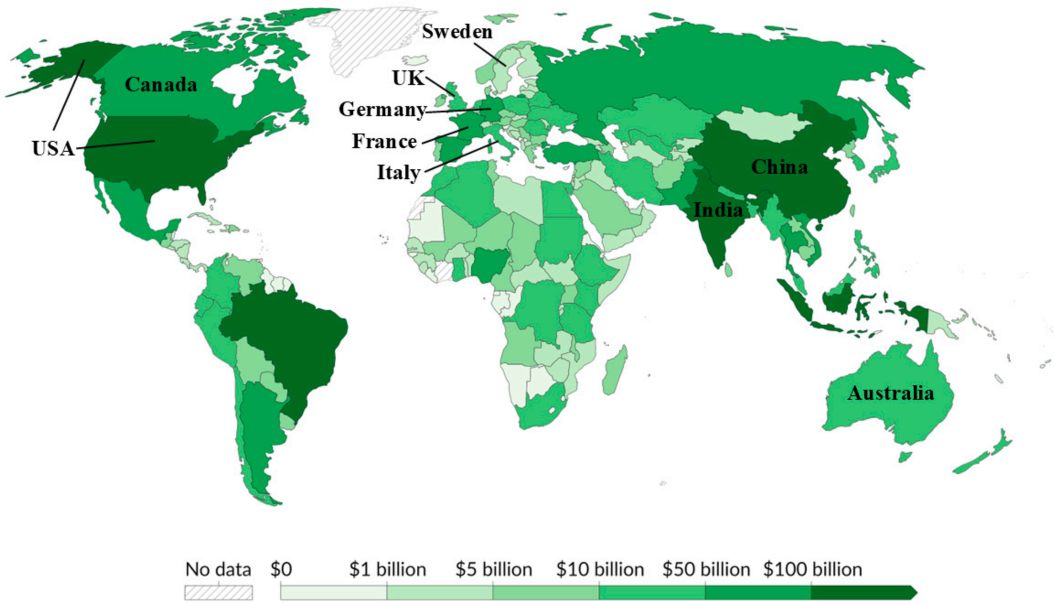


Figure 4. Distribution of agricultural output in the top 10 countries with publications in the field of fertilization's role on soil carbon sequestration.

3.2.2. Analysis of Author Collaboration

A bibliometric analysis of author collaborations identified key contributors to research on the role of fertilization in soil carbon sequestration and highlighted significant network of cooperation (Figure 5). The authors with a large number of publications included Kuzyakov Yakov (57 papers) from Göttingen University, Ge Tida from Ningbo University (33 papers), and Wu Jinshui from the Chinese Academy of Sciences (32 papers). Kuzyakov Yakov has made substantial contributions to the study of carbon sequestration and carbon and nitrogen cycles. Kuzyakov Yakov's team had strong academic collaborations with

Wu Jinshui, Ge Tida, etc. There were also two notable collaborative teams (Figure 5). Xu Minggang from Shanxi Agricultural University and Shen Qirong from Nanjing Agricultural University have formed a stable scientific research cooperation. In addition, Ding Weixin of the Chinese Academy of Sciences collaborated with a group of researchers at Zhejiang University. Although some smaller research teams or independent researchers are also contributing to this field, the increasing number of papers indicates that there is significant potential for further development in research on the effect of fertilization on soil carbon sequestration.

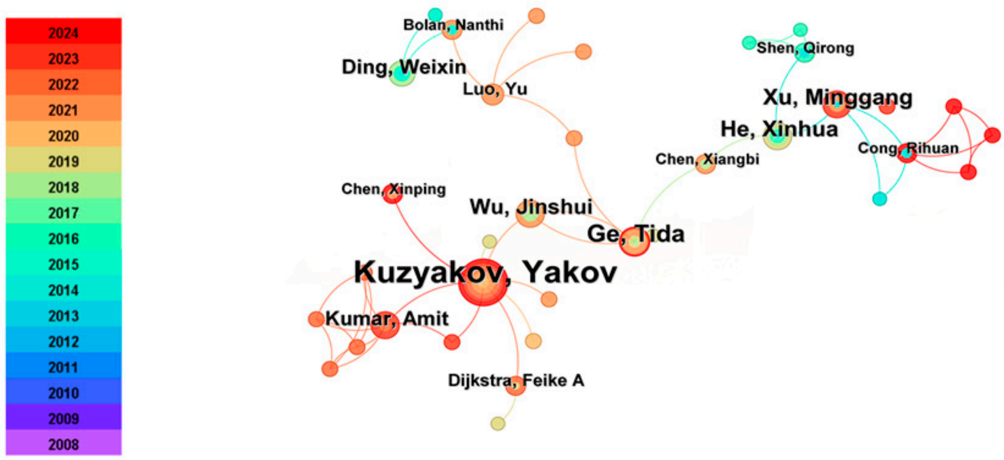


Figure 5. Network map of the author collaborations' analysis in the field of fertilization's role on soil carbon sequestration.

3.3. Analysis of Publishing Journals

From 2008 to 2024, a total of 439 journals published research on the role of fertilization in soil carbon sequestration (Table 3). *Agriculture, Ecosystems & Environment* (IF = 6.4) led the field with 149 publications, accounting for 5.11% of all papers. The journal emphasizes the importance of fertilization on ecosystem function and soil health. This was followed by *Science of The Total Environment* (142 counts, IF = 8.6), *Soil Tillage Research* (109 counts, IF = 6.9), *Agronomy Basel* (98 counts, IF = 3.7), and *Global Change Biology* (87 counts, IF = 13.0). These journals collectively highlight the pivotal role of sustainable agricultural practices and environmental management in addressing global challenges such as climate change and soil health. Notably, *Global Change Biology*, with its high impact factor, underscores the considerable influence of agricultural practices on climate change. The high publication volume and impact factors of these journals indicate that the role of fertilization on carbon sequestration is a significant area of research that has attracted the attention of a diverse range of disciplines, including soil science, environmental science, and plant science.

Table 3. Top 10 journals in terms of the number of published papers in the field of fertilization's role on soil carbon sequestration.

Rank	Journal	Counts	Centrality	Impact Factor
1	*Agriculture, Ecosystems & Environment*	149	0.05	6.4
2	*Science of The Total Environment*	142	0.03	8.6
3	*Soil Tillage Research*	109	0.02	6.9
4	*Agronomy Basel*	98	0.01	3.7
5	*Global Change Biology*	87	0.06	13.0
6	*Geoderma*	73	0.03	6.7
7	*Soil Biology Biochemistry*	62	0.05	10.4
8	*Journal of Cleaner Production*	55	0.01	10.2
9	*Plant and Soil*	54	0.04	4.6
10	*Journal of Environmental Management*	48	0.01	7.9

3.4. Crucial Literature

Crucial literature refers to key words that provide important insights or frameworks driving advancements in a research field. Studies with high centrality and citations represents the core theory and methodology of the research field and are the theoretical basis or reference for new research. Table 4 lists the crucial publications with the top 10 citation frequency and centrality greater than 0.04.

Table 4. Information of crucial publications in the field of the role of fertilization on soil carbon sequestration.

Rank	Title	Journal	First Authors	Centrality	Year
1	Soil carbon 4 per mille	*Geoderma*	Minasny, B	0.14	2017 [30]
2	The importance of anabolism in microbial control over soil carbon storage	*Nature Microbiology*	Liang, C	0.15	2017 [32]
3	Climate-smart soils	*Nature*	Paustian, K	0.10	2016 [4]
4	Long-term fertilization effects on soil organic carbon sequestration in an Inceptisol	*Soil & Tillage Research*	Ghosh, A	0.06	2018 [33]
5	Carbon sequestration in agricultural soils via cultivation of cover crops – A meta-analysis	*Agriculture, Ecosystems and Environment*	Poeplau, C	0.04	2015 [34]
6	Animal manure application and soil organic carbon stocks: a meta-analysis	*Global Change Biology*	Mallard, E	0.81	2014 [35]
7	Long-term effects of NPK fertilizers and organic manures on carbon stabilization and management index under rice-wheat cropping system	*Soil & Tillage Research*	Chaudhary, S	0.15	2017 [36]
8	Soil organic carbon storage as a key function of soils - A review of drivers and indicators at various scales	*Geoderma*	Wiesmeier, M	0.04	2019 [37]
9	Effects of long-term fertilization and residue management on soil organic carbon changes in paddy soils of China: A meta-analysis	*Agriculture, Ecosystems and Environment*	Tian, K	0.19	2015 [38]
10	The contentious nature of soil organic matter	*Nature*	Lehmann, J	0.18	2015 [39]

These crucial literatures were mainly concentrated between 2015 and 2019, which belonged to the development period. During this period, several pioneering studies laid the groundwork for future research. For example, Minasny, B et al. demonstrated that a 4‰ or even higher sequestration rate increase in SOC stock can be achieved under optimal soil management practices. The study emphasized the importance of considering the depth of soil profile in organic carbon sequestration studies, provided a reliable argument to validate the feasibility of the "4 per 1000" scheme, and clarified the role of improving agricultural soil management in promoting carbon sequestration and mitigating climate change. Liang et al. proposed the concept of "microbial carbon pump" (MCP), and elucidated how microbes influenced the content and stability of soil organic matter. They showed that microbial process, through extracellular vivo modification and in vivo turnover, control soil carbon storage, offering new mechanistic insights into how soil carbon dynamics response to global changes.

Two other key articles, with high centrality of 0.81 and 0.19, respectively, played an important role in bridging different research teams and topics. Mallard, E et al. quantified the response of SOC stocks to animal manure application, explaining over 53% of the variability in SOC stocks after manure application. This study provided theoretical support for improving SOC change factors in national greenhouse gas (GHG) inventories by accounting for manure-C input. Tian, K et al. simulated the changes of SOC under different manure application treatments and straw management at the regional scale. Their findings showed that the carbon sequestration potential of organic fertilizer and straw return was greater than that of no fertilization and provided a scientific basis for accurately estimating the change of SOC in China's paddy soils and their impacts for agroecosystem sustainability and carbon sequestration.

Other key studies mainly focused on the long-term effects of organic fertilizer application, integrated nutrient management, and soil types on the structure of microbial communities and SOC storage and cycling. These studies confirmed that fertilization played a crucial role in stabilizing the soil carbon pool and promoting soil carbon sequestration. From the research themes of the highly cited literature, it is evident that researchers consistently focus on the effects of fertilizer types and different fertilization management strategies on the structure and function of soil microbial communities, as well as the mechanisms governing SOC dynamics.

3.5. Keywords' Clustering Analysis

3.5.1. Keyword Analysis

Keywords provide a concise summary of the main research content and themes. In this study, the year per slice was set to 1 and TOP N was set to 50 in keyword co-occurrence visualization analysis (Figure 6), resulting in a total of 286 keyword nodes and 2944 co-occurring connections. The analysis showed that 'fertilization', 'carbon sequestration', 'nitrogen fertilization', 'soil organic carbon', 'microbial biomass' and 'organic matter' were the terms with high frequency. These keywords indicated the central focus of researchers on the interactions among various fertilizer management practices, microbial community dynamics, and soil physical and chemical properties. Recent research is increasingly exploring areas, such as the mechanisms of microbial community dynamic responses and soil health, which are beneficial for promoting sustainable agriculture and soil ecosystem development [6,40].

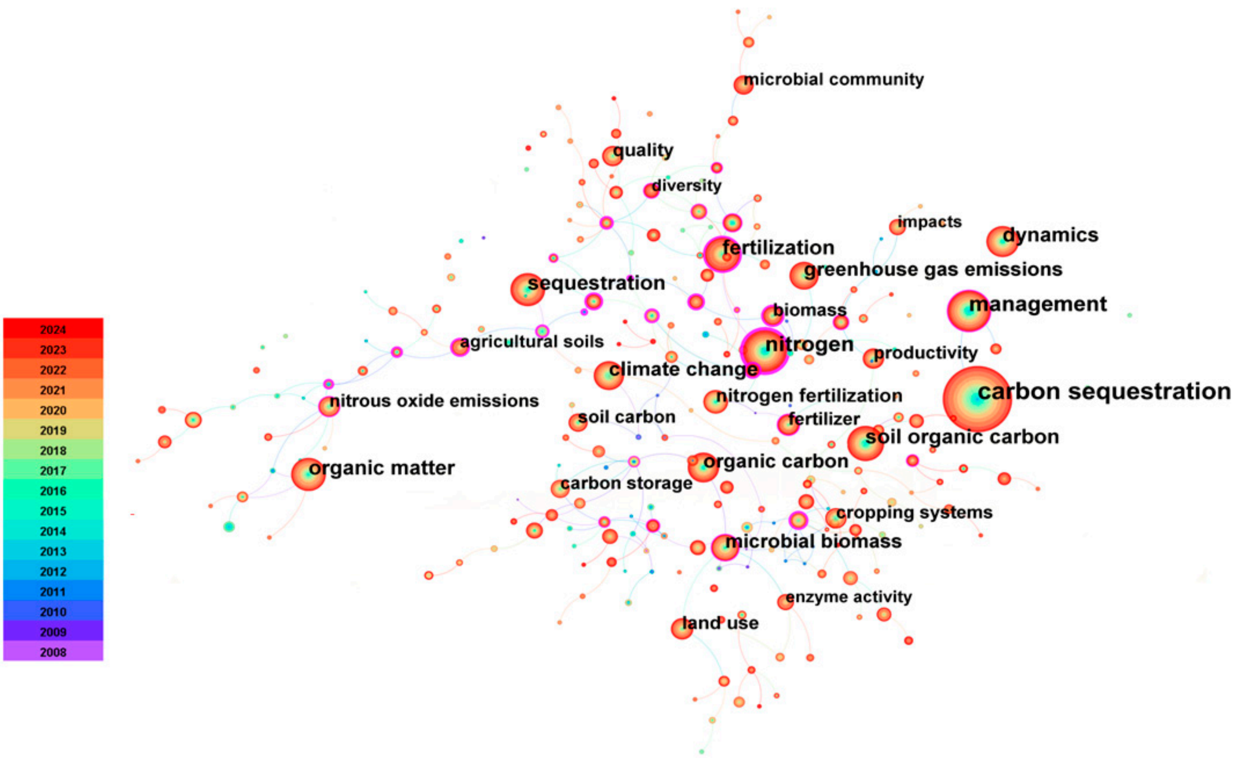


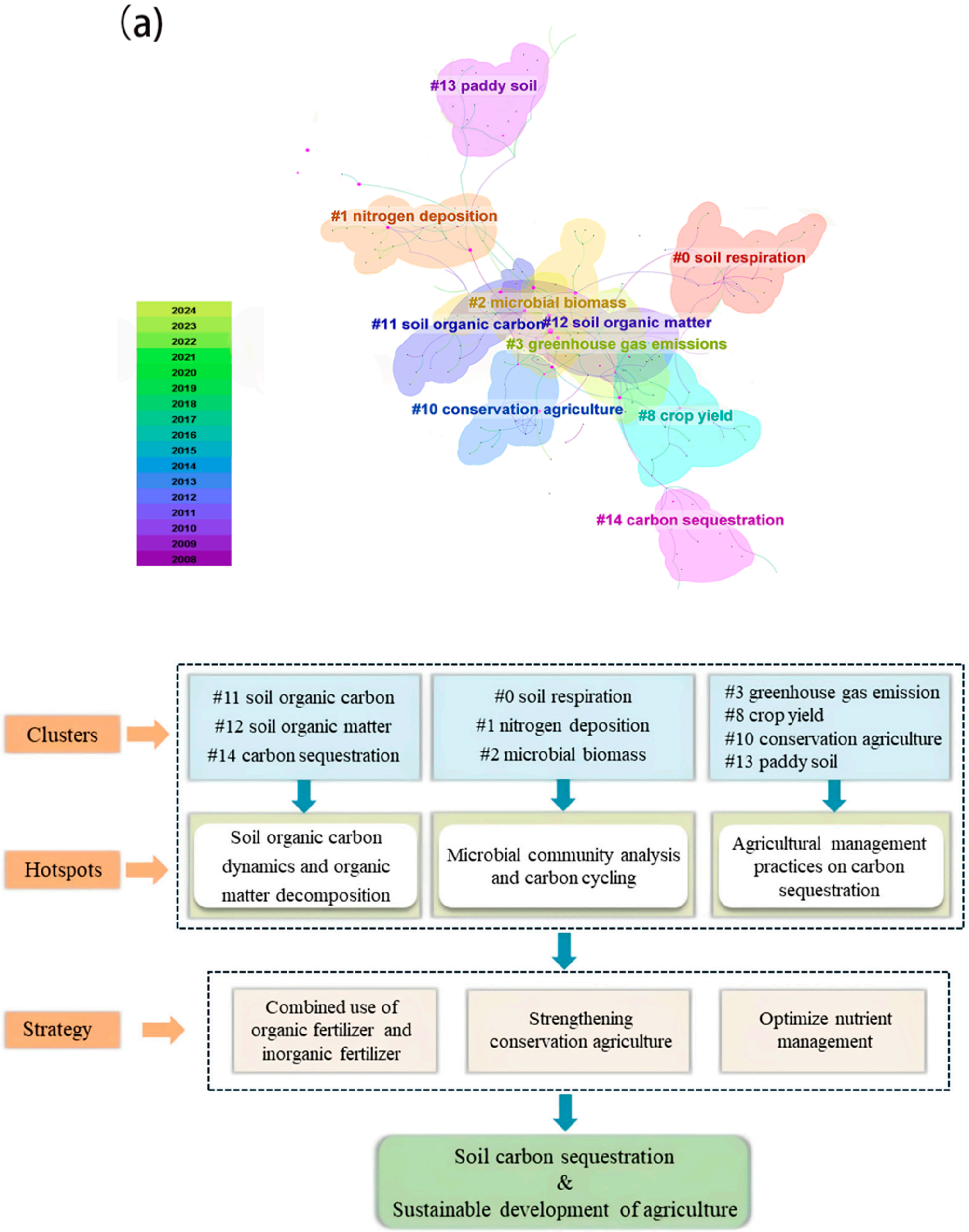
Figure 6. Co-occurrence of keywords on role of fertilization on soil carbon sequestration.

3.5.2. Hot Research Topics

In CiteSpace, the LLR clustering method allowed for further clustering of keywords based on their co-occurrence (Figure 6). The modularity (Q) and silhouette (S) values can be employed to assess the significance and rationality of clustering. For clustering results to be deemed valid, the modularity and silhouette values should exceed 0.5 and 0.7, respectively.

After removing clusters not relevant to the role of fertilization on carbon sequestration and keeping clusters with high correlation, 11 clusters were screened with Q = 0.8032 and S = 0.9343, which indicate that the clustering was reliable. Based on clustering results with high-frequency keywords, keywords related to the role of fertilization in soil carbon sequestration could be broadly categorized into three main research hotspots: (1) SOC dynamics and organic matter decomposition, (2) microbial community and carbon cycling, and (3) agricultural management practices on soil carbon sequestration (Figure 7).

(a)



(**b**)

Figure 7. Results of hotspot analysis. (**a**) Keyword clusters. (**b**) Construction of research hotspot frameworks.

1. SOC dynamics and organic matter decomposition.

The first research hotspot focused on the SOC dynamics and organic matter decomposition, including three clusters (#11, #12, #14). Soil organic carbon, a key element of soil organic matter, plays a significant role in enhancing soil structure, enhancing soil fertility, promoting microbial activity, and regulating climate change [40]. The content and stability of SOC are affected by several factors, such as manure addition and tillage practices. Previous studies showed that different fertilization practices can modify the levels of SOC and its labile fractions, as they can affect the balance between primary and decomposition carbon, which in turn influences the stability of the SOC pool [41]. Understanding changes in reactive organic carbon fractions is important for revealing carbon cycle processes and promoting the sustainable use of terrestrial ecosystems [42]. For example, Li, F et al. found that the application of multi-nutrient compost and crop rotation in low fertility soils significantly increased the concentrations of mineral associated organic carbon and particulate associated organic carbon, which was accompanied by improvement in soil structure, collectively enhancing the SOC stock and stability [43]. Zhang et al. demonstrated that soil microbial communities were closely related to different active SOC fractions under various fertilization practices and that the application of organic fertilizers effectively promoted the participation of soil bacteria and fungi in organic carbon turnover [44].

The priming effect of soil organic matter is also an essential mediator in the soil carbon cycle, which is critical for sequestrating carbon in the soil [45]. The addition of "fresh" organic matter can accelerate the mineralization of native soil organic matter, a process referred to as the "priming effect" (PE). The intensity of the priming effect can be changed by adding more or higher-quality organic matter [46]. Exogenous organic carbon and nitrogen inputs from fertilizer management are important factors in regulating the initiation effect as they balance the nutrient requirements for microbial growth [47]. For example, the priming effect in soil fertilized with a high C:N ratio is increased, as microorganisms produce extracellular enzymes to co-metabolize soil organic matter [48]. Xu et al. found that 50% organic fertilizer replacing the proportion of mineral nitrogen fertilizer enhanced SOC stability and showed the lowest cumulative initiation effect, which contributed to carbon sequestration and improved crop yield [49]. Therefore, a comprehensive understanding of carbon dynamics associated with different fertilization practices is essential for formulating effective agricultural strategies and enhancing soil carbon sequestration.

2. Microbial community dynamics and carbon cycling.

The second research hotspot focused on microbial community dynamics and carbon cycling, including three clusters (#0, #1, #2). The microbial community plays a pivotal role in regulating soil carbon cycling and bio-geochemical carbon processes [50]. Gaining insights into the crucial role of microbial communities in carbon cycling and storage can improve the effectiveness of agricultural management strategies. Different fertilization practices lead to various changes in soil physical and chemical properties as well as soil microorganisms, which in turn can affect the production and decomposition of SOC over time [51,52]. Organic fertilization could increase the substrate content in soil aggregates and enhance microbial activity within these aggregates, which are critical factors for improving soil carbon sequestration [53]. Most studies suggest that mineral fertilizers do not have long-term negative effects on soil microorganisms. Yuan et al. and Li et al. found that nitrogen and phosphorous addition could alter soil microbial parameters and inhibit soil microbial activity but had minor long-term effects on microbial activity and abundance [54,55].

Nitrogen fertilizer provides the elements needed for microbial and plant growth and alter the ecosystem carbon cycling, given that carbon and nitrogen are firmly coupled [56]. Generally, nitrogen addition can affect two main processes of carbon dynamics: carbon gains from plant growth and turnover and carbon loss from microbial decomposition. Investigating the response of SOC to nitrogen inputs is crucial for revealing the complexity of global carbon cycling. Xu et al. found that long-term nitrogen addition increased SOC content increased due to enhanced plant carbon inputs and reduced soil microbial biomass and respiration, which decreased carbon losses from decomposition [57]. In addition, nitrogen input affects soil organic matter decomposition, likely due to changes in enzyme activities due to shifts in microbial community [58]. Nitrogen addition promotes the growth of copiotrophic bacteria, which can effectively degrade labile substances by producing hydrolytic and oxidative enzymes, thereby influencing the decomposition of soil organic matter [59,60]. Nitrogen fertilizer could substantially alter soil microbial parameters and have a significant effect on soil microbial communities and their functions. For example, a study in agroecosystems showed that under long-term nitrogen fertilization, soil microbial biomass was positively correlated with SOC content when soil pH exceeded 5.0, with small changes in soil pH altering microbial community composition [61]. Nitrogen addition can reduce microbial N depletion in soil organic matter and improve microbial carbon use efficiency, without affecting total microbial biomass [58]. In summary, long-term nitrogen fertilization can enhance the soil's capacity for carbon sequestration, contributing to future climate change mitigation.

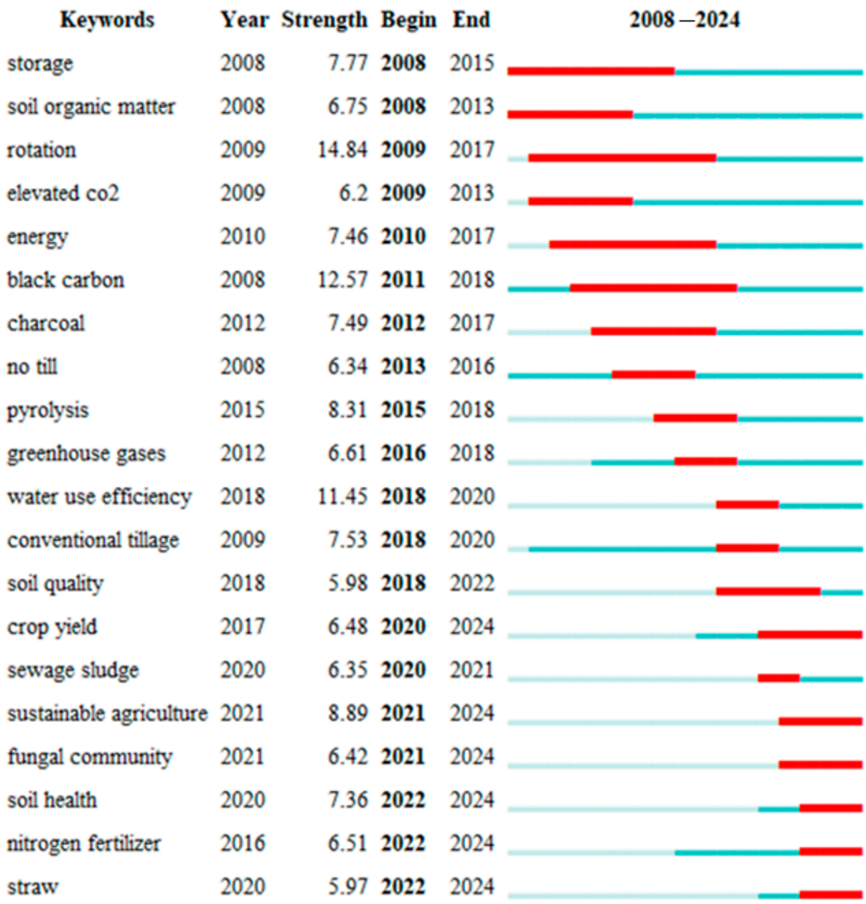
3. Agricultural management practices on carbon sequestration.

The most recent research hotspots focused on agricultural management practices and ecological impacts, including four clusters (#3, #8, #10, #13). Soil carbon sequestration capacity is affected by various soil management practices including tillage reduction and nutrient management [1]. Among them, the combined use of organic fertilizers and chemical fertilizers is an effective approach to enhance soil carbon sequestration [62]. Iqbal et al. showed that partial substitution of inorganic fertilizer through organic manure not only improves soil fertility and reduce inorganic fertilizer, but also increase soil carbon storage and crop yield [63]. In addition, various amendments are beneficial for enhancing soil carbon content. Liang et.al found that straw derived biochar had a significant effect on soil carbon sequestration, which greatly increased the surface SOC [64]. Meanwhile, processed and treated soil organic amendments can reduce greenhouse gas emissions including carbon dioxide, methane, and nitrous oxide. Bustamente et al. suggested that adding biodigestate to soil is one of the most effective biological ways to reduce emissions of greenhouse gases, especially carbon dioxide [65]. This approach not only helps return organic matter to the soil but also improves soil structure, water-holding capacity, and nutrient availability, which are critical for sustainable soil health and productivity [66]. Furthermore, amendments like compost, green manure, and even industrial by-products have been researched for their potential to not only sequester carbon but also improve soil fertility, plant growth, and overall ecosystem functioning, making them a focal area for achieving sustainable soil management practices and mitigating climate change [67,68].

Proper nutrient management is an essential part of sustainable agricultural management practices and can improve soil carbon sequestration efficiency. Sustainably maintaining soil health and productivity is essential for enhancing soil quality and increasing SOC content [8]. High carbon content can determine soil quality and crop yield, significantly impacting soil physio-chemical and biological properties. Improving the soil carbon pool through conservation agriculture is therefore necessary. Conservation practices, such as minimum tillage, permanent soil cover and crop diversification with optimal application management of inorganic fertilizers are effective strategies [69]. Optimal nutrient management under conservation agriculture can increase SOC concentrations and affect the distribution of organic carbon within soil profiles [70]. Combining conservation agriculture with balanced nutrient management enhances the concentration of SOC. Kirkby et al. demonstrated that balancing crop residue inputs with supplemental nutrients can maintain or even increase soil carbon content, regardless of different tillage practices [71] Additionally, it improves the stability of soil organic matter through an improvement in soil microbial diversity and enzymatic activities [72]. Enhanced biological activity is vital for the decomposition of organic matter and the synthesis of stable organic compounds, fostering a soil environment that effectively sequesters carbon over the long term and promotes overall soil health [73].

3.6. Research Frontiers

Burst words can be used to track the evolution of a field and forecast future research trends (Figure 8). These keywords represented emerging research topics in the role of fertilization in soil carbon sequestration. At the inception stage (2008–2014), 'storage' and 'soil organic matter' began to show strong burst strength, suggesting the importance of early studies focusing on the basic concepts of soil organic matter and carbon storage. In the next stage (2015–2019), high-intensity burst words comprised 'pyrolysis', 'greenhouse gases', and 'water use efficiency', suggesting that achieving soil carbon sequestration and reducing greenhouse gas emissions through advanced agricultural technologies became research priorities. After 2020, seven burst terms received significant attention, including 'ewage sludge', 'sustainable agriculture', and 'soil health'. These terms suggest a growing focus on waste recycling, sustainable agriculture, and integrated management of soil health.



Keywords	Year	Strength	Begin	End	2008–2024
storage	2008	7.77	**2008**	2015	
soil organic matter	2008	6.75	**2008**	2013	
rotation	2009	14.84	**2009**	2017	
elevated co2	2009	6.2	**2009**	2013	
energy	2010	7.46	**2010**	2017	
black carbon	2008	12.57	**2011**	2018	
charcoal	2012	7.49	**2012**	2017	
no till	2008	6.34	**2013**	2016	
pyrolysis	2015	8.31	**2015**	2018	
greenhouse gases	2012	6.61	**2016**	2018	
water use efficiency	2018	11.45	**2018**	2020	
conventional tillage	2009	7.53	**2018**	2020	
soil quality	2018	5.98	**2018**	2022	
crop yield	2017	6.48	**2020**	2024	
sewage sludge	2020	6.35	**2020**	2021	
sustainable agriculture	2021	8.89	**2021**	2024	
fungal community	2021	6.42	**2021**	2024	
soil health	2020	7.36	**2022**	2024	
nitrogen fertilizer	2016	6.51	**2022**	2024	
straw	2020	5.97	**2022**	2024	

Figure 8. Top 20 keywords with the strongest citation bursts derived from analyzed papers on the role of fertilization on carbon sequestration.

1. In recent years, the use of biochar and waste recycling have demonstrated significant potential in enhancing soil carbon sequestration capacity. Mainstream waste treatment methods such as incineration and landfills directly release carbon dioxide and methane, exacerbating the greenhouse effect and causing environmental pollution [74]. Future research should further integrate biochar with urban and agricultural waste to develop treatment models that are harmless, reductive, automated, and resource-utilizing. The carbon sequestration efficiency in different soil types can be improved by optimizing the pyrolysis process and improving the properties of biochar, ensuring pollution reduction and carbon sequestration without re-emission of carbon back into the atmosphere.

2. Under the backdrop of climate change, the importance of sustainable agricultural practices and soil health management in future research cannot be overstated. The necessity of leveraging sustainable agricultural practices has been emphasized by the International Panel for Climate Change, as it can help address the challenges posed by climate change and enhance ecosystem adaptability resilience [75]. Sustainable soil management practices can make significant progress in mitigating the climate crisis. However, soil degradation, driven by factors such as pollution, acidification, and salinization, remains a severe challenge [76]. Thus, optimizing and advancing agricultural soil management is crucial to achieving sustainable development goals. Moreover, research on sustainable soil use and management should prioritize soil health and address the relationship with important issues such as biodiversity and climate change. SOC is an important indicator for the assessment of soil health, reflecting the integrated state of soil's physical, chemical, and biological properties. As a result, increasing SOC content through sustainable agricultural practices, such as optimized fertilization strategies, crop rotation, and cover cropping, is key to reducing the climate crisis and improving agricultural productivity.
3. Soil microorganisms are central to maintaining SOC and nutrient cycling, controlling agroecosystem productivity and improving soil health. Agricultural practices such as cover cropping, organic amendments, and crop rotation not only alter microbial biomass and community structure but also affect SOC sequestration [77]. As a dynamic system, the soil ecosystem drives microorganisms to adopt strategies in response to climate change. Therefore, it is important to understand how different fertilization management practices affect the physicochemical changes in the metabolic and physiological characteristics of soil microbiomes. This is crucial for assessing the impact on net SOC sequestration and the mitigation of atmospheric greenhouse gas emissions. The interactions between soil, microorganisms, and climate change are increasingly gaining attention. The use of advanced molecular biology and ecological modeling techniques is highly encouraged to predict the potential and effectiveness of soil carbon sequestration under various agricultural practices.
4. In the context of global warming, future research on soil carbon sequestration will aim to develop innovative strategies that align with climate adaptability and sustainable agricultural systems. The integration of agroforestry, ecological practices, and regenerative agriculture can enhance soil carbon storage while also promoting biodiversity. Precision agriculture technologies, such as remote sensing and drone-based soil analysis, are expected to play a crucial role in optimizing soil carbon sequestration [78,79]. These tools enable more accurate monitoring of soil health, tracking of soil carbon fluxes, and site-specific management to improve carbon inputs while minimizing losses. Additionally, future research should emphasize the synergistic effects of multiple practices, such as combining cover cropping, diverse crop rotations, and organic amendments to maximize carbon sequestration potential [80]. Understanding how different environmental conditions, land use changes, and extreme weather events impact soil carbon storage is essential for ensuring the long-term stability and permanence of carbon sequestration.

4. Conclusions

Fertilization is an important factor affecting soil C sequestration. This study conducted a bibliometric analysis of 2347 papers published in the WOS from 2008 to 2024 to explore research development, content, hotspots, and emerging trends in this field. The following conclusions were drawn:

1. The field can be divided into three periods. The field is currently in the booming period, with an increasing number of relevant papers. China, the USA, Germany, and India published more papers in this field, and had a close collaboration with each other. The Chinese Academy of Science was the core institutions in this field. Agriculture Ecosystems Environment and Science of The Total Environment were

identified as the most influential journals. The ten crucial pieces of literature provided a theoretical foundation and reference for future research in this field.

2. The keyword clustering analysis revealed the three hotspots: SOC dynamics and organic matter decomposition, microbial community dynamics, and carbon cycling, as well as the impact of agricultural management practices on carbon sequestration. Those hotspots reflected the current research priorities and highlighted the close connection and synergy within soil carbon sequestration research.
3. Burst word analysis suggests that future research will increasingly focus on the utilization of biochar and resources, sustainable agricultural practices, and soil health management in the context of climate change, as well as on the role of microbial communities in soil carbon sequestration.

In summary, this study highlights the significance and evolution of research on the impact of fertilization on soil carbon sequestration. Future efforts should concentrate on more innovative agricultural practices and management strategies to achieve a win-win relationship between soil carbon sequestration and environmental climate improvement.

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