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Review

Trends and Hotspots in Soil Minerals' Impacts on Carbon Stability Research: A Bibliometric Analysis Based on Web of Science

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Abstract: The association with minerals is the most critical factor influencing the stability of organic carbon in soil. It is essential to gain an in-depth understanding of the research progress and future development trends regarding the impact of soil minerals on organic carbon stability both domestically and internationally and to identify current key issues; a total of 1834 research papers from the Web of Science Core Collection database were selected as the data source. These papers were examined using CiteSpace, HistCite, VOSviewer, and Origin 9.1 tools. The analysis categorized and visualized data based on countries, institutions, journals, disciplines, and keywords, utilizing indices like the number of articles and total/average citation frequency. The results indicate that the number of publications on the study of soil minerals and their impact on organic carbon stability has been increasing from 2013 to 2023. China and the United States have significantly led in the number of publications in this field. However, research collaborations among countries also exhibit significant regional characteristics. The Chinese Academy of Sciences (CAS) has the most publications. Yet, its average frequency of local citations is only 0.81 per paper, significantly lower than the top ten average of 2.23 per paper. The journal with the highest number of articles in this field is *Nature Communications*, with 248 articles. The main research hotspots focus on aspects such as the adsorption of organic carbon by minerals, catalytic transformation, and redox reactions. Future research should build on this foundation to focus more on detailed mechanisms, particularly the long-term effects of different environmental factors and time scales on soil carbon stability.

Keywords: soil minerals; organic carbon stability; bibliometrics; visualization; prospect

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1. Introduction

As a dynamic global carbon reservoir, soil contains more organic carbon than vegetation and the atmosphere [1]. The estimated global stock of soil organic carbon (SOC) ranges from 1500 to 1600 Pg (Pg = 10^{15} g) at a soil depth of 1 m, and from 2376 to 2456 Pg at a depth of 2 m [2] (Figure 1). The release or activation of even a small fraction of SOC can significantly impact atmospheric greenhouse gases and global climate. Approximately 14% of the atmospheric CO_2 increase in the last decade has been reported to be attributed

to SOC instability [3]. However, the combination of soil minerals with organic matter can effectively prevent the decomposition of organic matter. Soil minerals are a crucial component of soil carbon stocks, accounting for more than 60% of the total [4]. Particulate organic carbon (POC) primarily originates from partially decomposed plant residues and represents a relatively unstable organic carbon component. In contrast, mineral-associated organic carbon (MAOC) is mainly formed from recalcitrant microbial metabolites and residues, characterized by slow turnover and excellent stability [5]. Therefore, studying the stability of SOC from the perspective of soil minerals is of great significance for assessing global carbon stocks and the carbon cycle [6].

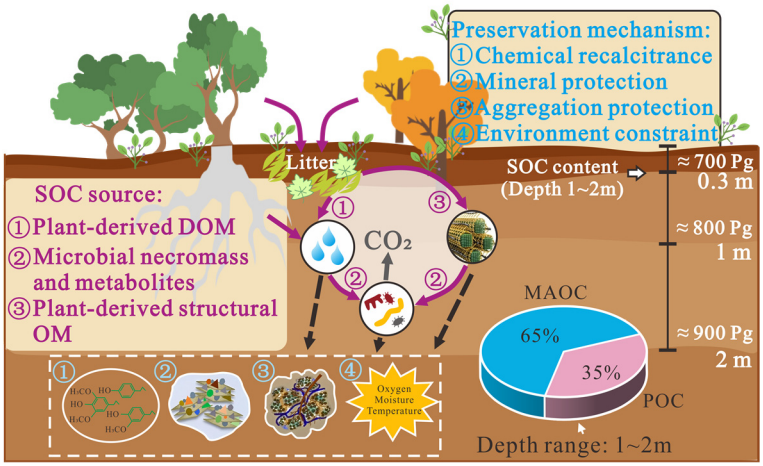


Figure 1. Global organic carbon stocks (modified from Feng et al. [7]). DOM: dissolved organic matter, OM: organic matter.

Earlier studies have indicated that carbon derived from above-ground plant residues is the soil's primary carbon source and regulates the rate of SOC accumulation [8]. Although it was previously believed that single molecular structures constituted "stable" SOC [9], advances in isotope tracing techniques have revealed that the so-called "stable" carbon pool contains a significant amount of SOC with unstable molecular structures, such as sugars and proteins [10]. Krull et al. [11] summarized SOC stability into two main mechanisms: biochemical resistance and physical protective effects. Later, Lützow et al. [12] further categorized three mechanisms: selective protection, spatial segregation of biological and SOC, and interaction with soil mineral surfaces and metal ions [13–16]. Among these, the interaction of SOC with soil minerals is widely recognized as the most stable mechanism [17]. Studies have confirmed that interactions with minerals can alter the morphology and properties of SOC through redox, polymerization, and catalytic reactions, directly affecting its stability and bioavailability [18–21]. Additionally, the association complexes formed through adsorption, complexation, and co-precipitation between SOC and minerals can protect SOC from being degraded [22–25]. The catalytic polymerization of SOC on mineral surfaces is considered a key step in preserving and accumulating SOC in soils [26,27]. Moreover, SOC can change the structure of minerals through chelation, solubilization, co-precipitation, and redox reactions, significantly affecting their combination with SOC, which is also crucial for the fate of SOC [28–30]. Despite numerous studies on how soil minerals affect SOC stability, there is a gap in the literature that analyzes and predicts future research directions or technological innovations in this field from the perspectives of changes in research trends and hot topics.

Using visual analysis tools such as CiteSpace [31], HistCite [32], and VOSviewer [33], along with bibliometric methods, this paper macroscopically quantifies the nature and direction of both domestic and international research on the impacts of soil minerals on the

stability of SOC over the past decade. By clustering, analyzing, and visualizing the retrieved literature, we reveal and describe the development history and structural relationships of scientific studies on the interactions between soil minerals and organic carbon from 2013 to 2023. It is important to note that this review adopts a bibliometric analysis approach, which differs from traditional narrative reviews. Unlike narrative reviews that focus on qualitative synthesis, bibliometric analysis relies on quantitative methods to systematically analyze large datasets of scientific literature [34]. As such, this paper includes detailed Section 2 to ensure transparency and reproducibility of the analysis. This study outlines the historical evolution and emerging trends in global research on the impact of soil minerals on carbon stability, identifies key gaps in current knowledge, and proposes potential directions for future research.

2. Materials and Methods

2.1. Data Collation

For this study, the Web of Science (WOS) Core Collection database under Clarivate Analytics was used as the source for literature searches, covering the period from 1 January 2013 to 30 October 2023. The search was executed on 1 December 2023, using the following subject search terms: TS = (carbon or soil organic matter or mineral-bound organic carbon) and (soil mineral or iron or aluminum or cadmium or barium or copper) and (microbial residue C or plant residue C) and (stabilizat or affect). The selected types of literature were research articles and reviews. A total of 1834 articles were retrieved and imported into HistCite, including contributions from 13,848 authors, 307 journals, and 96,307 references.

2.2. Statistical Method

This paper employed various analytical tools (Figure 2), including the built-in analysis tool of the WOS database, CiteSpace literature visualization [31], HistCite citation analysis software [32], VOSviewer [33]. In the application of HistCite [32], the key parameters are the Total Local Citation Score (TLCS) and the Total Global Citation Score (TGCS). CiteSpace and VOSviewer were used to extract important noun phrases from the titles, abstracts, and keywords of the documents for co-word, co-occurrence, and emergent term analysis. This is to identify the research focus and trends regarding the role of soil minerals in organic carbon stability [31]. The analysis in CiteSpace covered the time span from 2013 to 2023, with a time node of one year and the discipline category as the node type. The node strength was set to Cosine by default, the threshold was TOP [25], and Pathfinder and Pruning Sliced Networks in the network pruning function area were selected for conducting the map analysis. VOSviewer was used to analyze countries and keywords, with the data type selected from WOS and the counting method set to Full counting. The keyword parameter threshold was set to 54 to generate the final map. Data analyzed by HistCite, VOSviewer, and CiteSpace were all from the articles downloaded in text format from the WOS database. Please note that this study is based on 1834 documents from the WoS database, potentially omitting relevant studies from other sources (e.g., Scopus, Google Scholar). Future research could integrate multiple databases and apply text mining and NLP to further explore topic evolution and key technological advances.

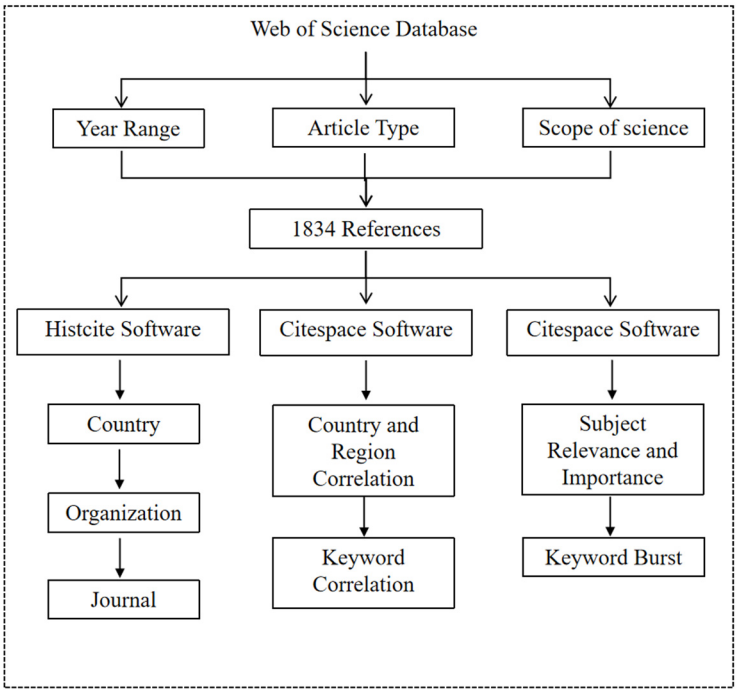


Figure 2. Data analysis flowchart.

3. Results and Discussion

3.1. Trends in the Number of Publications

Changes in the number of publications can effectively indicate research intensity in a particular field over a given period, providing great significance for analyzing the development dynamics during that period and predicting future trends [35]. The global atmospheric CO_2 concentration surpassed 400 mg/L for the first time in 2013 [36], after which the number of publications concerning the topic of this study showed an approximately linear increase (Figure 3). According to Raza et al. [2], 64% of the 46,080 SOC-related publications were published within the last decade (2014–2023). As shown in Figure 3, publications on the influences of minerals on SOC stability have steadily increased over the past decade. The year 2022 saw the highest number of publications, reaching 232, and by 2023, the cumulative number of publications had reached 1834. Publications in this field accounted for 4–8% of SOC-themed publications in the past decade. Several global initiatives have been launched with discussions on increasing SOC inventories as a potential solution for climate change mitigation, including the "4 pour 1000" initiative (https://4p1000.org, accessed on 7 December 2024), RECSOIL (https://www.fao.org/global-soil-partnership/areas-of-work/recarbonization-of-global-soils, accessed on 7 December 2024), the Koronivia Joint Work on Agriculture (https://www.fao.org/koronivia, accessed on 7 December 2024), the REDD+project (https://www.fao.org/redd/overview/en/, accessed on 7 December 2024), and the European Soil Strategy. These initiatives have effectively promoted research on the role of minerals in stabilizing organic carbon, making the interaction between minerals and SOC an increasingly popular topic in global soil carbon research. Moreover, the growing number of academic achievements in this field indicates a deepening understanding among researchers regarding the effects of minerals on organic carbon stability.

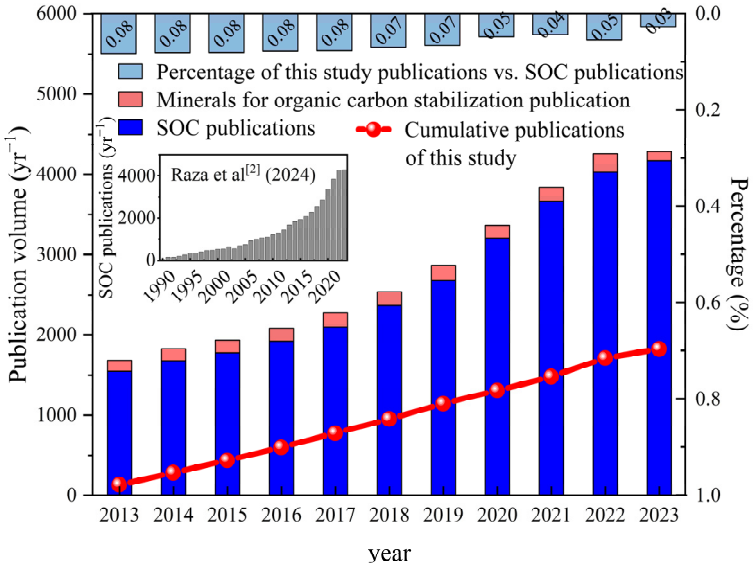


Figure 3. Annual number of publications and cumulative number of publications during 2013–2023 [2].

3.2. Top 10 Countries/Regions in Terms of Total Number of Publications

The number of publications (records) in a particular field of research can indicate the level of interest in this research field among different countries and reflect current global trends in advanced research. Additionally, the number and frequency with which a region's or country's articles are indexed and cited by the Science Citation Index (SCI) reveal the overall scientific research capacity and influence of that country or region in the field [37]. In the WOS Core Collection database, research papers on the impacts of soil minerals on organic carbon stability were retrieved from 108 countries/regions. These countries/regions include the United States, China, Germany, the United Kingdom, and Japan, with a primary concentration in Europe, East Asia, and North America (Figure 4). As shown in Table 1, from 2013 to 2023, the United States published 846 articles, achieving the highest total citation frequency (1385 times), thereby demonstrating its dominant position in this research field. China ranks second globally in terms of the number of publications, with a total of 673 articles, which is 428 more than Germany, the third-ranked country. This indicates that the United States and China are leading significantly in the number of publications in this field. This is consistent with the findings of Raza et al. in their global soil carbon research [2]. The results of scientific papers, policy direction, and financial support reflect the dominance of these two countries in this field. China, a populous country with a developed agricultural economy, emphasized green agriculture and sustainable development in its 14th Five-Year Plan. This initiative aims to reduce global carbon emissions [38]. The United States, as a developed country, boasts numerous high-level research institutions and researchers, holding significant academic influence globally [38]. In addition, the publication volume by country indicates that researchers with a high focus on this field are primarily concentrated in developed countries. This is mainly due to these countries' strong research capabilities, abundant natural resources, and a high demand for addressing global issues such as climate change. Research institutions and universities in these countries have advanced experimental facilities and stable funding support (as illustrated in Table 2). At the same time, their diverse geographical and ecological environments provide varied conditions for studying the interactions between soil minerals and SOC. Among these countries, the total local citation score per research paper (TLCSPR) in China (0.71) is lower than the world's top ten average of 1.01. This suggests that Chinese research papers in this field are less influential. Canada and the United States have the highest total local citation score per research paper, with values of

1.84 and 1.64, respectively. Furthermore, China's total global citation score per research paper (TGCSPR) is 231.82, ranking ninth among the top ten countries. This also reflects the gap between China and the United States.

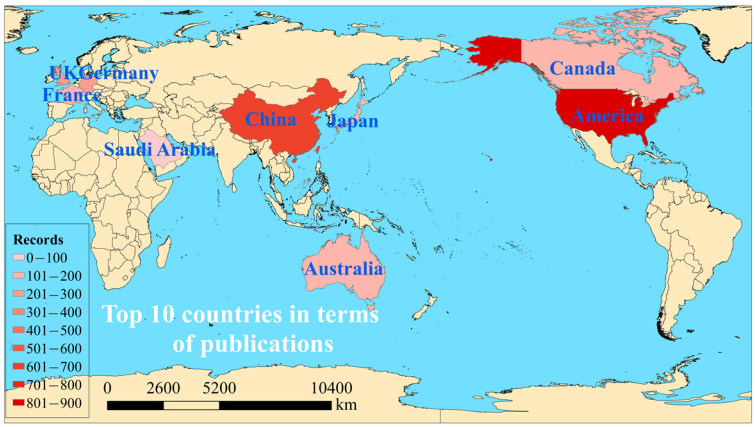


Figure 4. Distribution of top 10 countries in terms of number of publications.

Table 1. Top 10 countries in research on the impacts of soil minerals on organic carbon stability from 2013 to 2023.

Country	Records	Total Local Citation Score (TLCS)	Total Local Citation Score per Research Paper (TLCSPR)	Total Global Citation Score (TGCS)	Total Global Citation Score per Research Paper (TGCSPR)
USA	846	1385	1.64	291,602	344.68
China	673	479	0.71	156,013	231.82
Germany	245	324	1.32	72,253	294.91
UK	228	164	0.72	59,700	261.84
Japan	129	158	1.22	43,746	339.12
Australia	124	50	0.40	33,501	270.17
France	121	74	0.61	28,870	238.60
Canada	103	190	1.84	35,800	347.57
Switzerland	103	147	1.43	30,626	297.34
Saudi Arabia	91	19	0.21	14,463	158.93

Table 2. Top 10 institutions researching the impacts of soil minerals on organic carbon stability from 2013 to 2023.

Institution	Records	Total Local Citation Score (TLCS)	Total Local Citation Score per Research Paper (TLCSPR)	Total Global Citation Score (TGCS)	Total Global Citation Score per Research Paper (TGCSPR)
Chinese Academy of Sciences	176	142	0.81	49,833	283.14
Stanford University	78	211	2.71	29,181	374.12
University of California, Berkeley	76	319	4.20	29,542	388.71
University of Chinese Academy of Sciences	62	47	0.76	16,700	269.35
Massachusetts Institute of Technology	51	51	1.00	21,763	426.73
California Institute of Technology	49	123	2.51	13,714	279.88
Lawrence Berkeley National Laboratory	46	161	3.50	13,904	302.26
Columbia University	45	167	3.71	20,739	460.87
Harvard University	43	69	1.60	22,383	520.53
Tsinghua University	40	61	1.53	12,259	306.48

In this study, the VOSviewer visual analysis tool (version 1.6.20) was employed to analyze the collaborative relationships in the field of soil minerals' impacts on organic car-

bon stability research between China (including Taiwan) and countries worldwide. Nodes represent keywords. The node size represents the number of occurrences of keywords. The threshold value of keyword parameters is set to 54; that is, keywords appear at least 54 times. Different colors represent different clusters. The size of the circles in the figure indicates the level of activity and the number of articles published by a country or region. In contrast, the distance of connecting lines between countries or regions represents the closeness of their cooperation, with shorter distances indicating closer collaboration. As shown in Figure 5, in this field, countries do not work in isolation—those with higher publication volumes tend to collaborate more closely, reflecting a shared commitment to soil pollution remediation. Figure 5 further illustrates the differences in regional cooperation, showing that China and the United States lead the research in this field. China collaborates more closely with countries in the Asia-Pacific region, whereas the United States has stronger cooperation with Western countries. International collaboration has shown distinct regional characteristics, and future international cooperation and knowledge sharing in this field still need to be further enhanced.

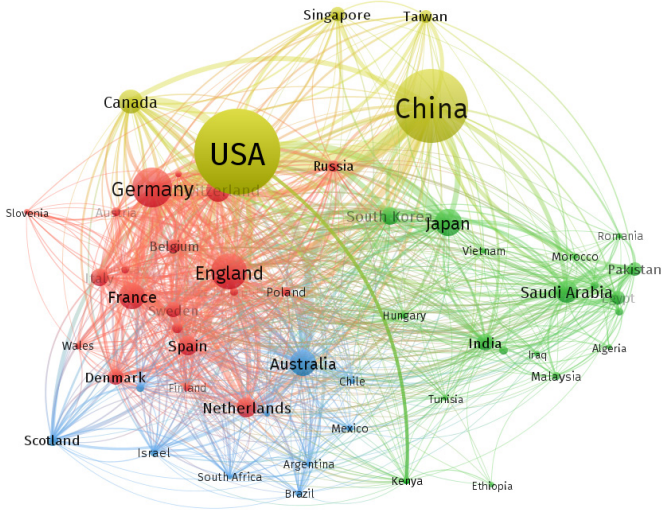


Figure 5. Cooperation between China (including Taiwan) and other countries in the field of research on the impacts of soil minerals on organic carbon stability from 2013 to 2023.

3.3. Key Research Institutions

According to the results from the citation analysis software HistCite, research papers on the impacts of soil minerals on organic carbon stability involve a total of 1266 research institutions. The top 10 research institutions in terms of the number of publications were analyzed. As shown in Table 2, research institutions from China and the United States dominate the top 10 list in terms of the records (number of publications). Three Chinese institutions—Chinese Academy of Sciences (CAS), University of Chinese Academy of Sciences, and Tsinghua University—are included in the top 10 list, with CAS leading significantly by publishing a total of 176 articles, indicating its high academic activity in this field. The rest are all research institutions from the United States. The ranking of institutional publication volume explains the differences in publication volume between countries. In terms of TGCS, CAS ranks first with 49,833 citations, followed by the University of California, Berkeley, with 29,542 citations, both demonstrating strong academic influence. However, considering the indicator of TLCSPR, CAS, despite having a higher number of publication records, has only 0.81 citations per paper, significantly lower than the average of the top 10 institutions (2.23 citations per paper). This suggests that CAS, as a representative of China's research institutions, still lags behind European and American research organizations in terms of the quality of academic papers.

3.4. Main Publication Journals

An in-depth analysis of journals within a particular field of study allows for the identification of core SCI source journals in that field. Table 3 lists the top 10 journals with the most articles published in the field of soil minerals–organic carbon stability. In 2020, the journal with the highest impact factor was *Nature*, at 64.8, followed by *Science* and *Nature Communications*, with impact factors of 56.9 and 16.6, respectively. *Scientific Reports* has the lowest impact factor among these journals, at 4.9. *Nature Communications* has the highest number of publications in this field. The top three journals in terms of TGCS are *Nature Communications* (77,630), *Nature* (63,463), and *Science* (44,760), indicating that these journals are highly influential in this field.

Table 3. Top 10 journals with the most publications in the field of soil minerals' impacts on organic carbon stability research from 2013 to 2023.

Journals	Records	Total Local Citation Score (TLCS)	Total Global Citation Score (TGCS)	Important Factor (5 Years)	Important Factor (2020)	Country
Nature Communications	248	190	77,630	17	16.6	UK
Nature	146	214	63,463	60.9	64.8	UK
Science	112	223	44,760	54.5	56.9	USA
Proceedings of The National Academy of Sciences of The United States of America	71	194	22,750	12	11.1	USA
Journal of The American Chemical Society	69	237	24,154	15.1	15	USA
Scientific Reports	56	70	9966	4.9	4.6	UK
Angewandte Chemie-International Edition	47	115	14,114	15.3	16.6	Germany
Science Advances	31	113	6027	15.4	13.6	USA
Frontiers in Plant Science	29	83	3458	6.8	5.6	Switzerland
Advanced Science	27	61	4261	16.7	15.1	USA

3.5. Discipline Co-Occurrence Analysis

As can be seen from the co-occurrence analysis mapping of the primary disciplines (Figure 6), among the top ten disciplines, aside from Geoscience and Environmental Engineering, the other eight disciplines have larger red outer circles. This reveals that there has been a parallel development across these disciplines and a rapid growth rate in multidisciplinary fields in recent years. Additionally, the dense connecting lines between disciplines indicate that research on the impact of soil minerals on organic carbon stability exhibits characteristics of interdisciplinary integration and close interrelation.

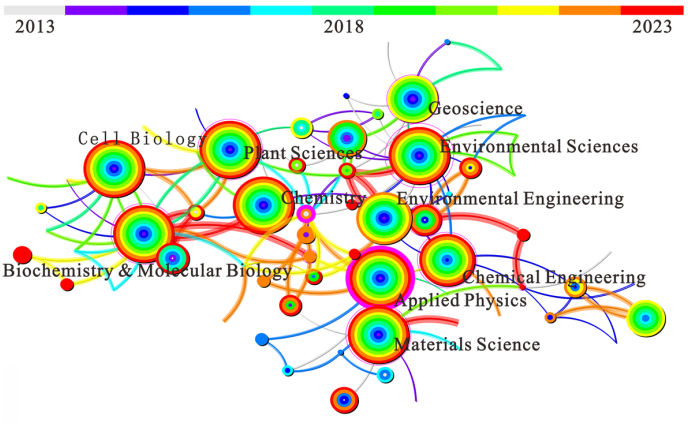


Figure 6. Analysis of main disciplines involved in research on the impacts of soil minerals on organic carbon stability from 2013 to 2023.

Figure 7 illustrates the frequency and centrality of various disciplines related to the impacts of soil minerals on organic carbon stability. The parameter set in CiteSpace is centrality, which can reflect the importance of a node within the system; stronger centrality indicates greater importance. Despite Chemistry having a high number of publications, its centrality is only 0.09, indicating that the impacts of soil minerals on organic carbon stability are not a primary research focus within this discipline. In contrast, Environmental Sciences has a centrality of 0.63, significantly higher than that of other disciplines. This suggests that Environmental Sciences serves as a crucial hub for interdisciplinary integration and connection. However, the cumulative number of publications in this discipline over the past ten years is only 136, indicating substantial potential for further research on the impacts of soil minerals on organic carbon stability. The low frequency and high centrality of environmental science in this field suggest that its research potential needs to be further explored. Research on organic carbon stability within environmental science has received widespread attention, such as the source of plant litter, occlusion within aggregates, incorporation in organo-mineral complexes, and location within the soil profile. Wetlands under different hydrological conditions [39] and the impacts of various natural and anthropogenic disturbances [40] have been studied. However, the regulatory mechanisms of environmental factors on minerals and SOC interactions and the effects of minerals on organic carbon stability under climate change, land use changes, and pollutant interference still require further research.

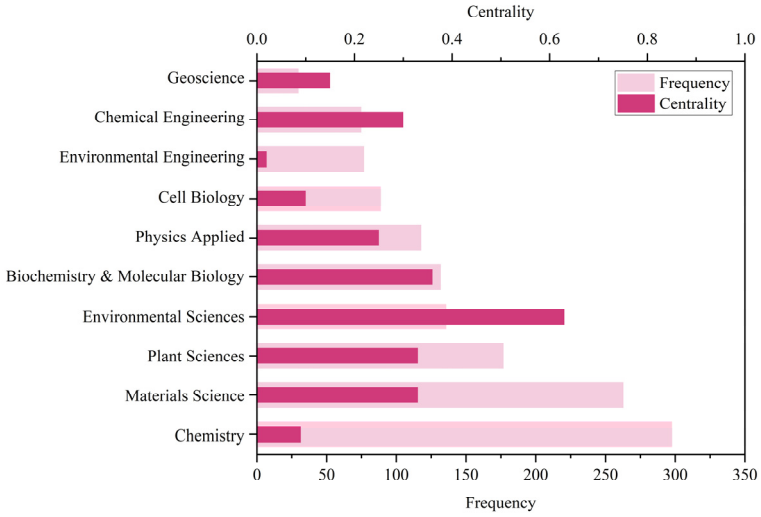


Figure 7. Centrality analysis of disciplines engaged in research on the impacts of soil minerals on organic carbon stability from 2013 to 2023.

3.6. Analysis of Research Hotspots and Frontiers at Home and Abroad

3.6.1. Research Hotspots at Home and Abroad

The keyword co-occurrence network model (Figure 8) was constructed using VOSviewer, a literature visualization and analysis software. By analyzing the keywords, researchers can gain insights into current research hotspots and future trends in the field [41]. In VOSviewer, keywords with a frequency of occurrence greater than six were visualized and analyzed. Among these, the keyword with the highest frequency of occurrence was "iron", appearing 563 times.

In the co-occurrence network model, the size of each circle represents the importance of each keyword; larger circles indicate higher frequency and greater significance within the research direction. The different colors of the circles represent different clusters to which the keywords belong. From Figure 8, it is evident that the keyword co-occurrence network is divided into six clusters. The six clusters are further summarized into two major categories:

"direct effects of minerals on organic carbon stability" and "indirect effects of inputs (quantity, quality) and degradation of vegetation production on organic carbon stability".

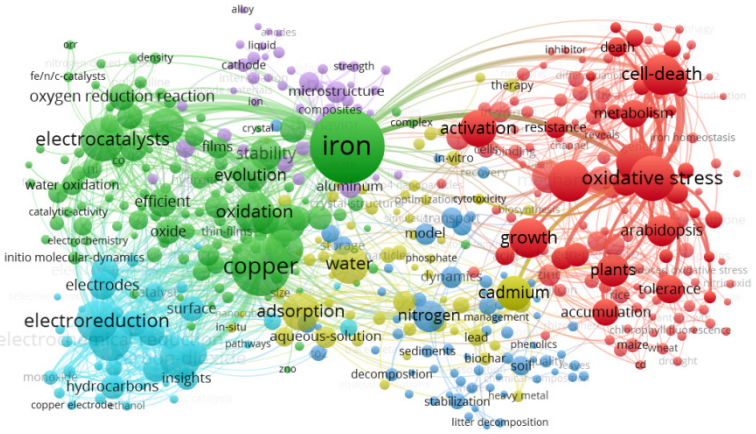


Figure 8. Distribution of research hotspots on the impacts of soil minerals on organic carbon stability from 2013 to 2023 in China.

The core terms within the green cluster are "iron", "catalyst", and "efficient". This cluster primarily focuses on the mineral-mediated catalytic conversion of SOC. Research has proved that minerals, acting as catalysts, can increase the reaction rate without altering the overall standard Gibbs free energy change of the reaction [42]. This effect can be attributed to three main aspects. First, minerals increase the concentration of SOC and oxidants, accelerating the reaction rate [43,44]. Secondly, minerals provide vacant electron orbits to accept bonded electron pairs from SOC or act as proton donors/acceptors to catalyze the reaction [45,46]. Thirdly, transition-metal-based mineral oxides or doped minerals can promote catalytic functions through cyclic valence changes and electron transfer [47–49]. In particular, redox-active iron minerals play crucial roles in many biogeochemical pathways [12,14]. As shown in Figure 7, there has been a growing interest in recent years in studying the effects of iron minerals on the stability of SOC. Clay minerals with different properties exhibit varying capacities to protect SOC. While laboratory studies indicate that the mass of clay minerals plays a crucial role in SOC protection, further mechanistic studies are still needed to explore this aspect [50]. In the future, efforts should be made to have a more comprehensive understanding of the function of minerals and the contributions of soil minerals to the transformation of SOC.

The core vocabularies within the light blue cluster include "electroreduction", "electrodes", "hydrocarbons", and "surfaces". This cluster focuses on the interactions between SOC and redox-active minerals. The direct electron transfer reactions between SOC and minerals and the indirect processes for the formation of reactive oxygen species (ROS) or microorganisms are essential interactions in the soil environment. First of all, although SOC encompasses a diverse range of surface functions from oxidation to reduction, it typically acts as an electron donor in redox reactions with soil minerals, resulting in the reduction of mineral metals. Additionally, redox reactions between soil minerals and SOC can generate ROS. These ROS, including hydrogen peroxide, superoxide, and hydroxyl radicals, are crucial in the process of SOC oxidation. They influence the molecular size, the presence of oxygen-containing functional groups, and the degree of SOC mineralization [51–53], depending on the specific reactants and conditions [42].

The core words and expressions within the yellow cluster are "adsorption", "aqueous-solution", and "cadmium". This cluster focuses on exploring the mechanisms of mineral adsorption of SOC. In natural soil systems, metal ion adsorption typically occurs through reactions with organic compounds, metal (oxygen) hydroxides, and clay mineral surfaces [54].

According to the research findings, entropy-driven hydrophobic repulsion, van der Waals forces, or hydrogen bonding may be the primary mechanism of adsorption under specific conditions [55,56]. For example, regarding electrostatic attraction, electrostatic bonding between soil mineral surfaces and organic molecules can occur through cation exchange. This reaction occurs when positively charged organic molecules, such as protonated amines, replace inorganic cations on the exchange complex [57]. The adsorption process generally begins with the formation of a monolayer on the mineral surface, which then evolves into a multilayer molecular structure driven by complex biological and chemical processes [58]. The mineral adsorption of SOC often determines the stability of SOC in the soil environment. This is why the adsorption mechanism predominates in the research [59]. Additionally, different metals exhibit varying affinities for different mineral species. For instance, cadmium, a heavy metal, is toxic to soil biota and is one of the most common metal pollutants in the soils of industrial, agricultural, and even urban areas [60,61]. Consequently, the adsorption effect of heavy metals on SOC has been extensively studied in recent years. This is due to the severe pollution of global water resources by heavy metals [62]. At the same time, adsorption offers advantages over other technologies, such as simplicity in operation, small footprint, stable effects, low cost, and great regeneration potential [63,64]. While various laboratory studies suggest that the quality of the clay minerals plays an important role in SOC protection, this has not been investigated by more mechanistic studies. Some existing literature indicates that the type of reactive mineral surfaces controls the mode of organic matter (OM) adsorption and assumes that bonding mechanisms control the turnover period [50].

For the purple cluster, the core terms include “microstructures”, “cathodes”, “crystals”, “ions”, and “composites”. This group focuses on the interactions between mineral ions and SOC, mainly in the form of co-precipitation. Co-precipitation is a key process in the association of SOC with soil minerals, akin to adsorption. However, the mixtures formed through co-precipitation play a more critical role in the cycling of carbon and mineral elements than those formed through adsorption [65]. Negatively charged mineral surfaces repel organic anions, but multivalent cations in the exchange complex facilitate their binding. In neutral and alkaline soils, Ca^{2+} and Mg^{2+} are the dominant cations, while in acidic soils, hydroxy polymers of Fe^{3+} and Al^{3+} predominate [50]. These positively charged ions are adsorbed onto negatively charged mineral surfaces and promote the adsorption of negatively charged long-chain organic molecules through cation bridging [12,66,67]. Unlike Fe^{3+} and Al^{3+} ions, Ca^{2+} ions do not form strong coordination complexes with organic ions. However, cation bridging interactions are weaker than ligand-exchange-mediated adsorption in OM binding [68,69]. Generally, the organic carbon (OC) adsorption sequence on clay minerals follows the order of oxides–hydroxides > 2:1 clay minerals > 1:1 clay minerals, a trend controlled by the SSA and CEC of the respective minerals.

The core terms for the red and blue clusters are “plants”, “oxidative stress”, “cell-death”, “activation”, “nitrogen”, “dynamics”, “litter decomposition”, and “sedimentation”, respectively. These clusters focus on the indirect effects of vegetation growth and degradation on the stabilization of SOC. It is commonly believed that most of the humic materials in soil are closely associated with the surfaces of colloidal minerals. Evidence for this comes from the following findings: organic materials associated with fine particles and clay [70–72] are older and have longer turnover times than those associated with sand particles [73,74]. According to Xu Jiahui et al. [74], the chemical properties of vegetation litter, such as lignin content, are major factors determining its degradation rate. Among abiotic regulatory factors, reduced soil moisture and changes in soil nitrogen and phosphorus content due to warming may promote plant root growth [75], thereby increasing carbon inputs. However, reduced moisture also decreases SOC chemical stability [76],

exacerbating its loss. On the other hand, under normal environmental conditions, plants maintain balance by regulating the production and removal of ROS. This balance can be disrupted by various abiotic stress factors, such as heavy metals [77]. Consequently, ROS levels can be used to monitor the extent of oxidative stress in plants.

A deeper review of the research hotspots reveals that existing studies primarily focus on several key areas, including the catalytic transformation of SOC mediated by minerals, redox reactions between SOC and active minerals, co-precipitation of mineral ions and SOC, the mechanisms of mineral adsorption on SOC, and the indirect effects of plant decomposition and formation on the stabilization of SOC. These directions highlight the central role of minerals in soil carbon stability research, providing clear focal points and a systematic framework for research in this field. Clay minerals with different properties exhibit varying capacities to protect SOC, making it difficult to determine the contribution of minerals in various mechanisms. Although several laboratory studies indicate that the quality of clay minerals plays an important role in SOC protection, this has yet to be explored through more mechanistic research [50]. Some existing literature suggests that the type of reactive mineral surface controls the adsorption pattern of OM and hypothesizes that bonding mechanisms control the turnover cycle. While this hypothesis holds true for in vitro studies, where residence time is related to desorption potential, long-term studies do not examine the correlation between specific bonding mechanisms and carbon turnover time. Furthermore, the existing knowledge based on time series mostly suggests a correlation between OC turnover time and the abundance of certain mineral phases. However, such studies cannot exclude the potential influence of factors such as soil aggregation, anoxia, and changes in microbial ecology on C turnover [50]. Therefore, this focus also implies that other potential mechanisms or environmental variables, such as the synergistic effects between microbes and minerals [78], the dynamic behavior of amorphous minerals [79], and the minerals and SOC interactions under climate change [80], may be relatively overlooked in current research trends. To address this, we suggest that future research could combine high-resolution characterization techniques (such as synchrotron X-ray absorption spectroscopy, nuclear magnetic resonance, etc.) and long-term incubation experiments to reveal further how different minerals influence the stability mechanisms of SOC.

3.6.2. Analysis of Research Frontiers

Emergent keywords are terms that appear suddenly and are frequently cited, used for analyzing research frontiers and hotspots over different periods [81]. Specifically, "begin" and "end" denote the start and end of a keyword's emergence period, respectively, while "strength" signifies the intensity of its emergence; a higher number indicates a more influential keyword [82]. Using the keyword burstiness analysis in CiteSpace software (version 6.3.R1), the detection model in the Control Panel was configured as follows: $f(x) = \alpha e^{(-\alpha x)}$, with $\alpha 1/\alpha 0 = 2.0$, The Number of States set to 2, $\gamma[0,1] = 1.0$, and Minimum Duration = 2. The top ten most frequently cited keywords were calculated based on this configuration. The keyword emergence analysis of literature on the impact of soil minerals on organic carbon stability is summarized in Figure 9. Among these, keywords such as "Electroreduction", "Hydrocarbon", "Lipid peroxidation", "Cell death", and "Protein" have shown a higher intensity of emergence after 2013, with values of 8.07, 7.83, 5.49, 5.22, and 4.47, respectively. These values reveal the current research hotspots in this field to a certain extent.

As mentioned above, different scholars hold varying views on the stabilization mechanisms of SOC in the soil. Nonetheless, the binding of SOC to minerals is recognized as a primary stabilization mechanism [12,14,16]. This binding involves several aspects, including ligand exchange, multivalent cation bond bridges, complexation, and van der Waals forces [12,13]. The main minerals contributing to OM stabilization in soil environments

include phyllosilicates (layered aluminum silicates, commonly referred to as clay minerals), metal oxides, hydroxides, and hydroxy-oxides (such as hematite, goethite, and pyroxenes), as well as short-range ordered aluminosilicates (such as opal, imogolite) [83]. Iron oxide minerals are favored over other mineral species for their larger specific surface area, more substantial adsorption capabilities, and higher preservation potential [12,14]. Therefore, they are regarded as some of the soil minerals that play a key role in the stabilization of SOC [13,84], and their content directly affects the soil's ability to adsorb SOC [16]. Additionally, numerous studies have demonstrated that Fe (III) oxides promote SOC degradation through direct or catalytic redox reactions [85–88]. Recent advancements in isotope tracing techniques have revealed that the carbon pool contains significant amounts of SOC with unstable molecular structures. These less stable organic carbons are more susceptible to degradation during redox processes with soil minerals, forming organic molecules with smaller sizes and richer O-functional groups [89,90]. Moreover, reactive-mineral-mediated processes can promote the mineralization of SOC through redox reactions, rather than protecting the soil environment [51,91]. For instance, data from Swedish forest soil surveys indicate that exchangeable Mn concentrations are negatively correlated with SOC content due to the oxidative decomposition of recalcitrant organic carbon by Mn peroxidase, which obscures conservation and production effects [87]. Electroreduction and iron oxide highlight the critical role of redox reactions on mineral surfaces in the adsorption, transformation, and protection of SOC. Hydrocarbon and protein emphasize the selectivity and diversity of interactions between different organic carbon molecules and minerals, influencing their stability. Lipid peroxidation and cell death further show how biological factors and their metabolic products regulate the minerals and organic carbon system through environmental chemical processes. These associations suggest that research should focus on the interfacial reactions between minerals and SOC, the coupling of biological and chemical processes, and the differential effects of various molecular types on stability to gain a more comprehensive understanding of the dynamic mechanisms of soil carbon stability.

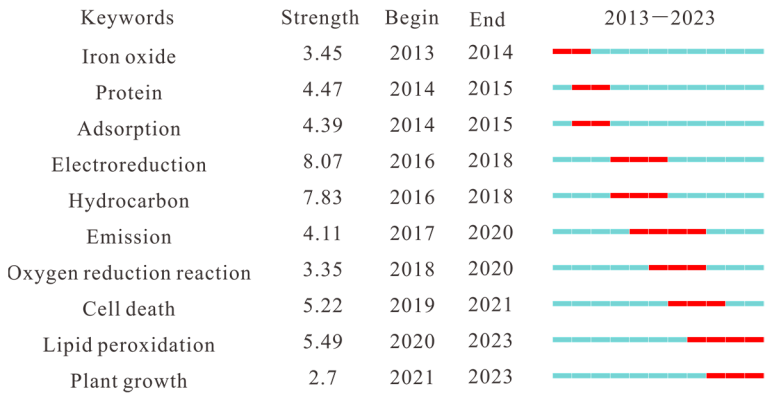


Figure 9. Keyword emergence from 2013 to 2023 (Red represents the start and end years).

As analyzed above, all these properties contribute to the high citation frequency of these keywords in the analysis of the impacts of soil minerals on organic carbon stability. In other words, these keywords have represented the frontiers and hotspots in the field of SOC stability research, particularly the interaction mechanisms between SOC and soil minerals, in the past ten years.

4. Conclusions

This paper presents a systematic bibliometric analysis of the research on the impact of soil minerals on SOC stability included in the WOS database from 2013 to 2023. Overall, research in this field shows an increasing trend, with a total of 1834 publications. The research

focuses on aspects such as the adsorption of SOC by minerals, catalytic transformation, and redox reactions. It is important to emphasize that with advancements in data analysis technology, future research could utilize methods such as knowledge graphs and deep learning to build more intelligent models for identifying and predicting research hotspots, thereby enhancing the depth and accuracy of the analysis. The specific conclusions are as follows:

(1) Global Research Trends and Collaboration: Research on the stability and interactions of soil minerals and SOC has continuously grown worldwide, particularly in Asia, Europe, and North America. While China and the United States lead in publication volume, research collaboration among countries shows distinct regional characteristics. Specifically, China collaborates more closely with countries in the Asia-Pacific region, while the United States primarily cooperates with European and North American countries. Nevertheless, there remains significant potential for further enhancement of international cooperation and knowledge sharing in this field.

(2) Major Research Institutions and Journals: The Chinese Academy of Sciences leads global research in this field, followed closely by the University of California, Berkeley. Regarding journal publications, *Nature Communications*, *Nature*, and *Science* are the most frequently cited journals in this area, indicating that research in this field has reached the international forefront.

(3) Co-occurrence Analysis: Environmental science is highly central to research on the impacts of soil minerals on organic carbon stability, serving as a key intersection between disciplines. However, over the past decade, research publications in this field have been relatively few, with only 136 papers, suggesting that environmental science's potential has not been fully realized. Future research should strengthen interdisciplinary collaboration between environmental science, chemistry, cell biology, and other fields to promote a deeper exploration of the mechanisms underlying the impacts of soil minerals on organic carbon stability.

(4) Research Themes and Future Directions: Current research primarily focuses on the mineral-mediated catalytic transformation of SOC, redox reactions, co-precipitation mechanisms, and adsorption mechanisms. However, some research gaps remain, such as the multi-factor interactions between minerals and SOC, the role of amorphous minerals, and the impact of environmental changes (e.g., climate change) on carbon stability. Future research should emphasize these complex interaction mechanisms, particularly the long-term effects of different environmental factors and time scales on soil carbon stability.

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