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Organic carbon in the climate crisis: a decade of bibliometric insights into global trends, gaps, and sustainable pathways

Highlight

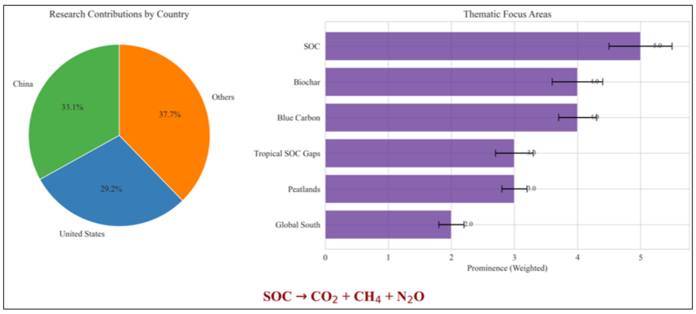
I. Organic carbon drives and mitigates climate change.

II. SOC sequesters CO_2 but human activity disrupts balance.

III. Post-Paris, OC research surged, peaking in 2021.

IV. Biochar and Blue Carbon key but need scalability.

Global South research gaps highlight collaboration need.



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Abstract

Organic carbon (OC) is a critical yet paradoxical component of Earth's climate system, simultaneously driving and mitigating climate change. This study synthesizes insights from 516 articles published between 2012–2022 to evaluate global scientific efforts addressing OC's role in climate change and global warming from Web of Science Core Collection. Using advanced bibliometric mapping, we analyze research trends, collaborations, and underrepresented domains. Soil organic carbon (SOC), the largest terrestrial carbon reservoir, regulates atmospheric CO_2 but is destabilized by deforestation, land-use change, and rising temperatures, exacerbating emissions when disturbed. Following the 2015 Paris Agreement, OC-related research surged by 42%, peaking in 2021 amid global carbon neutrality pledges. China (33.05%) and the United States (29.22%) led publication output, while European nations like Denmark demonstrated exceptional collaborative networks, underscoring the value of international partnerships. Emerging strategies such as biochar application and coastal ecosystem conservation show promise for carbon sequestration but face economic and policy implementation barriers. Critical gaps persist in understanding OC dynamics in vulnerable tropical regions and northern peatlands—key carbon sinks that remain understudied. Furthermore, limited inclusion of Global South perspectives and insufficient interdisciplinary collaboration impede equitable, context-specific solutions. This study emphasizes the urgency of fostering global cooperation to address spatial and disciplinary disparities, aligning research with policy frameworks to meet the 1.5°C climate target. Prioritizing the protection of carbon-rich ecosystems, advancing sustainable land management, and scaling nature-based solutions are vital. By bridging geographical and institutional divides, OC research can catalyze transformative, collaborative action to enhance climate resilience and achieve carbon neutrality, ensuring equitable progress toward global sustainability goals.

Keywords: Organic Carbon (OC), Soil Organic Carbon (SOC), climate change mitigation, bibliometric analysis, nature-based solutions, global south

Introduction

The Earth's climate system is intricately related to the global carbon cycle, in which organic carbon (OC) acts as both a driver and a mitigating factor of climate change.[1] Photosynthesis in terrestrial and marine ecosystems is a key carbon sink that absorbs atmospheric CO_2 and stabilizes world temperatures.[2,3] However, anthropogenic activities—including fossil fuel combustion, deforestation, and intensive agriculture—have disrupted this equilibrium, releasing approximately 110 billion tons of carbon annually and elevating global surface temperatures by 0.9°C since the pre-industrial era.[4] This imbalance underscores the urgency of managing carbon sinks, such as forests and soils, to offset emissions and mitigate warming trends.

Central to this issue is soil organic carbon (SOC), the greatest terrestrial carbon store, containing an estimated 2,700 gigatons (Gt) globally—triple the carbon content of the atmosphere and plants combined.[5,6] Soil organic carbon (SOC), comprising 58% of soil organic matter, regulates greenhouse gas dynamics by governing carbon mineralization and anaerobic degradation pathways. It also acts as a long-term carbon sink, mitigating atmospheric CO_2 levels.[7,8] SOC's dual roles as a source and reservoir of greenhouse gases highlight its critical influence on global climate systems, emphasizing the need for sustainable soil management to balance carbon emissions and sequestration.[9,10] Yet its stability is threatened by environmental factors: rising temperatures accelerate microbial decomposition, converting stored carbon into CO_2 or methane and exacerbating global warming through feedback loops.[11,12] Land-use practices like tillage, urbanization, and peatland drainage destabilize soil organic carbon, releasing greenhouse gases, contributing 12-15% of global CO_2 emissions.[13,14] Sustainable land management is crucial to preserve SOC stocks and mitigate climate impacts.[15]

These disruptions manifest in cascading ecological crises, including glacial melt, sea-level rise, and extreme weather events, which jeopardize biodiversity, food security, and human livelihoods. International efforts, such as the Paris Agreement and national carbon neutrality pledges, aim to curb emissions by 2050. Novel approaches to carbon sequestration and climate resilience have surfaced, such as the use of biochar and the maintenance of Blue Carbon (BC) ecosystems, which focus on seagrass beds, mangroves, and coastal wetlands. Critical gaps still exist despite advancements.[16] With a disproportionate emphasis on temperate regions and little integration of socioeconomic issues, research on SOC dynamics is still fragmented. Furthermore, the underrepresentation of research from the Global South impedes the development of equitable and context-specific remedies.

This study uses CiteSpace to analyze research trends, partnerships, and knowledge gaps from 2012 to 2022 in organic carbon-climate research. The investigation focuses on the progress of organic carbon-climate research, geographical and institutional differences in research output and collaboration, and significant hurdles preventing successful organic carbon management for climate mitigation.

The popularity of nature-based and technology solutions for carbon neutrality is expected to rise beyond 2020. However, regional imbalances and fragmented methodologies persist. This paper presents practical recommendations for safeguarding soil oxygen content (SOC), expanding biochar usage, and promoting global collaboration to align carbon management with the 1.5°C climate objective.

Data and methods

Eligibility criteria and processing

A bibliometric analysis was conducted to evaluate the role of organic carbon in global warming and climate change, following the PRISMA framework (Figure 1). The initial search identified a large corpus of literature, with 12,007 records sourced from the Web of Science (WoS) Core Collection and an additional 18,500 records from Google Scholar. After removing duplicates and screening titles and abstracts for relevance, 9,905 articles from WoS were assessed for eligibility. A subsequent rigorous full-text review refined this pool, ultimately identifying 516 qualified articles published between 2012 and 2022 for the final quantitative synthesis. Data processing and visualization were performed using CiteSpace (v6.1R6) and VOSviewer, with records exported to plain text and Excel for systematic analysis.[17,18] This transparent selection process underscores the growing interest in organic carbon dynamics, highlights regional biases and knowledge gaps, and promotes informed decision-making through the consistent application of PRISMA standards.[19]

Scientometrics analysis

This scientometric study employed CiteSpace (v.6.1.R6) as outlined by Liang et al. (2021) to analyze 9,905 articles published between 2012 and 2022 from the Web of Science, focusing on global research trends regarding the role of organic carbon in climate change.[20] The study analyzed publication trends, identified core themes like soil carbon sequestration and biochar, highlighted leading contributors from the U.S., China, and EU, and detected emerging frontiers like blue carbon ecosystems.[21] Post-2015, research on carbon-climate feedback increased, revealing geographic bias towards temperate ecosystems. CiteSpace visualizations facilitated interdisciplinary connections, and linking research.[22–24] The data for the CiteSpace analysis comprised 9,905 papers on theory and practice published from January 1, 2012, to December 31, 2022, with a total of 345,833 unique references sourced from the Web of Science.

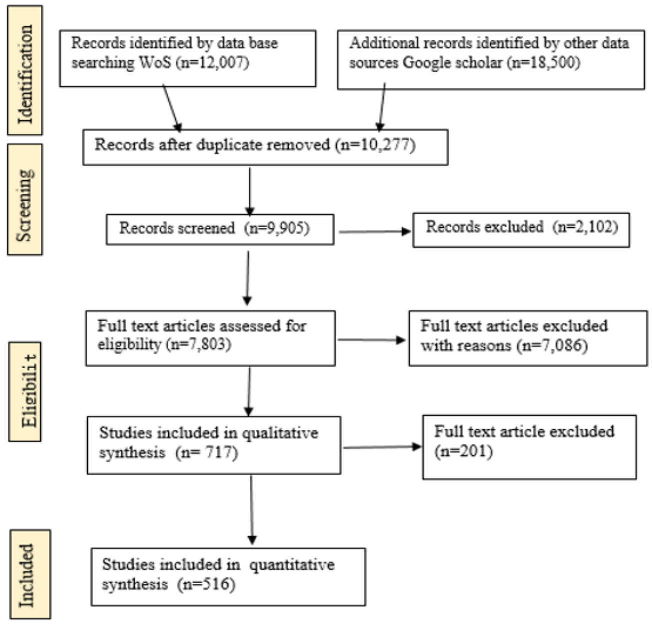

Figure 1 Flow Diagram detailing PRISMA from 2012 to 2022.

Bibliometric network analysis framework

Bibliometric networks are analyzed using VOSviewer and CiteSpace, emphasizing the significance of strength, degree, and link in understanding relationships within scientific literature.[25] The analysis begins with network construction and graphs, with VOSviewer assessing relationship strength, CiteSpace assessing centrality, and a temporal and burst analysis.[26]

Bursts, trends, and their influence

CiteSpace's burst detection and multi-perspective analysis aid in understanding research trends over time, automating data processing, and identifying underrepresented tropical ecosystems. This tool aligns studies with global challenges like climate mitigation, promoting evidence-based science and policy through quantitative metrics.[17] The "multiple-perspective co-citation analysis" method was used to analyze a work with high burstness, focusing on structural, temporal, and semantic patterns (Table S1).

Selection of nodes

CiteSpace uses two network analysis methods such as Top N per slice and g-index, which indicate the number of articles required to get g^2 citations.[27] The dataset is divided into yearly segments. The g-index dynamically identified significant nodes based on citation impact, with a predefined threshold for highly cited works. The network showcased the top 10 most cited or referenced entities within each annual slice, highlighting sustained impact over raw citation numbers.[28]

Network development

The study utilized the Web of Science database to create co-citation networks for organic carbon and climate change research trends, utilizing Author (ACA), Document (DCA), and Journal Co-

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citation Analysis (JCA) methodologies and keyword co-occurrence mapping. Temporal metrics like burstiness and citation degree track research focus, while structural metrics like modularity, centrality, and silhouette scores confirm the strength of thematic groups like soil carbon and oceanic cycles. For example, high modularity (Q>0.3) and silhouette scores (>0.7) confirmed distinct, high-quality clusters, while centrality highlighted foundational works linking carbon cycles to climate models.[29,30] The study utilized both quantitative and qualitative methods to identify climate science publications that highlighted policy changes and underrepresented ecosystems.

Visualization and labeling

To illustrate the evolution and connections of research themes, we used two complementary methods: a timeline view and a cluster view.[31] The timeline view organized biochar studies chronologically, while the cluster approach connected nodes across historical periods, illustrating thematic linkages and the impact of fundamental concepts like soil carbon modeling on agroforestry carbon storage, and objectively categorized these clusters.[28] The study utilized dual visualization and data-driven labeling to label a cluster of terms like "peatland," "methane," and "thaw" as "Permafrost Carbon Feedback," transforming complex citation networks into clear research development maps over a decade.

Results and discussions

Analysis of research trend

The analysis of publication trends from 2012 to 2022 provides important insights into the changing academic focus on the role of organic carbon in global warming and climate change. A total of 12,007 peer-reviewed articles were published, with 10,277 of them being in English (95% of their total output from 2012–2022) (Figure 1). Annual publication numbers steadily increased until 2021, exceeding 1,500 articles per year, indicating a growing global interest in scientific research and policy. However, there was an unexpected drop in 2022 (Figure 2a), which may be attributed to data delays or changing priorities after the pandemic. Initially, research was primarily focused on soil science (16.61%) and marine biology, with England and Bangladesh standing out as key contributors—the former working on policy frameworks and the latter concentrating on vulnerable ecosystems like mangroves. After 2019, the emphasis shifted significantly towards climate change adaptation and organic carbon reserves, influenced by IPCC reports and commitments to net-zero emissions. Environmental Sciences led the way (41.3% of studies), followed by Multidisciplinary Geosciences (18.78%) and Soil Science (16.61%) (Figure 2b). Research emphasizes Arctic and blue carbon habitats' importance for carbon storage, recommending scalable solutions like improved trading systems, fair pricing, and interdisciplinary collaboration in underrepresented areas.

The number of published studies on organic carbon and global warming/climate change is strongly linked, indicating progress. China and the USA dominate the world in terms of publication number and citation due to their significant contributions to global emissions.[32,33] The US spends more on research than any other country, yet China has the most researchers working in universities and corporations. However, their publication degrees and bursts are lower than England.[34] It highlighted the global reach and impact of this research. The primary areas of focus evolved over time, with Environmental Sciences, Multidisciplinary Geosciences, and Soil Science emerging as the leading topics.[35] The review analyzes citation counts and article relevance using rigorous exclusion criteria, focusing on key models like BRT, soil erosion, CiteScore, bibliographic coupling, and organic carbon modeling community (Figure 2).[36]

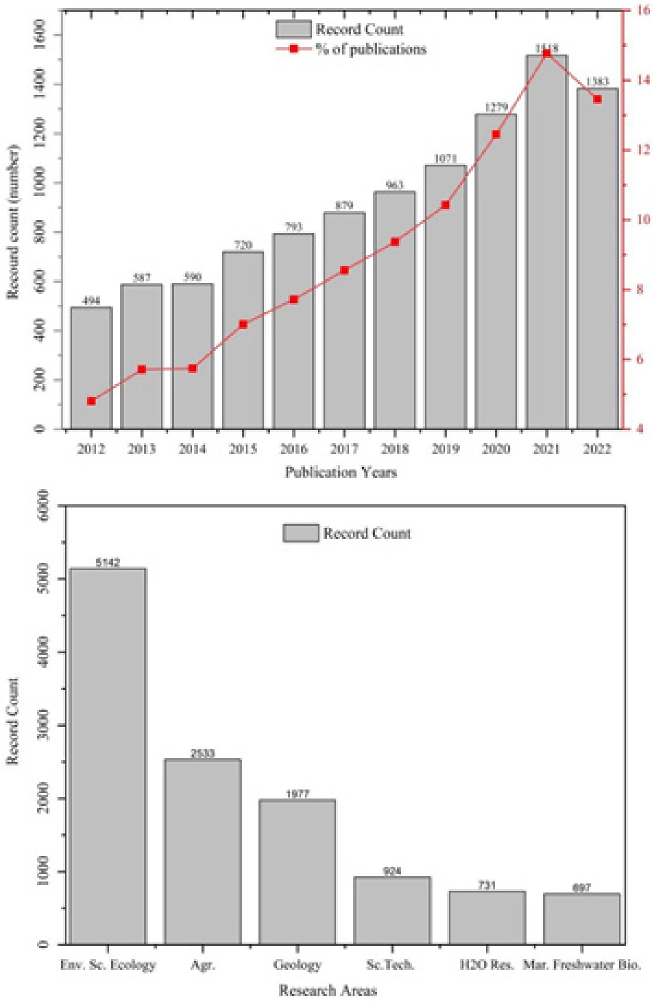

Figure 2 Analysis of Research Trend; (a) Trend in changes in the number of published papers, (b). Study areas.

The organic carbon modeling community should prioritize understanding uncertainty, performance evaluation, and standardization to standardize and evaluate carbon trading systems.[37,38] Research from the same nation or region is often cited by researchers. The Arctic region experienced the highest warming trends from 2012 to 2022, with 2022 being the fifth-warmest year on record. Soil is the largest terrestrial organic carbon store, and soil quality impacts atmospheric carbon concentrations. Research surges due to social, political, and scientific factors, necessitating institutional cooperation for climate-friendly technology and filling gaps in the Earth System Model and Qinghai Plateau Cluster.[39]

Analysis of research cooperation network

Analysis of research countries' collaboration

This study examined international research contributions on organic carbon and climate change from 2012 to 2022, highlighting significant collaboration among 151 countries (with a 96% cooperation rate) through a network comprising 156 nodes and 1,299 connections (density=0.146, (Figure 3). China led in both output (3,396 publications, 33.05%) and citations (3,245), closely followed by the United States with 2,913 citations (Figure 3a), emphasizing their crucial roles in advancing this field (Table S2). Notably, Denmark emerged as the most influential collaborator (degree centrality=48), surpassing major contributors like France (47) and Switzerland (47), which underscores its vital role in connecting research communities. After 2017, China and the U.S. further established their leadership, driving significant advancements in organic carbon dynamics and greenhouse gas mitigation (Figure 3b). At the same time, Bangladesh (burst strength = 6.35, 2021–2022) and Ethiopia (5.05, 2020–2022) rose as important voices, especially in climate-vulnerable regions, reflecting an increasing focus on localized impacts (Table 1). Early contributors like England laid the groundwork for climate change research, with recent activity from Bangladesh and Egypt indicating a shift towards areas disproportionately affected by climate extremes. However, significant gaps remain in studies on tropical farmland and environmental variables integration (Figure 3c, Table 1). European nations excel in Arctic research, but tropical ecosystems are underrepresented, highlighting the need for equitable partnerships to address geographic and thematic imbalances and align science with global climate resilience objectives.

Table 1 Top 10 Countries with the strongest citation bursts

Countries	Year	Strength	Begin	End	2012 - 2022
England	2012	10.09	2012	2012	
Bangladesh	2013	6.35	2021	2022	
Ethiopia	2012	5.05	2020	2022	
Egypt	2012	4.29	2021	2022	
Venezuela	2013	4.1	2013	2015	
Mexico	2012	3.31	2012	2012	
Zimbabwe	2015	3.27	2015	2016	
Madagascar	2014	2.85	2016	2018	
Nepal	2014	2.84	2019	2019	
Italy	2012	2.64	2012	2012	

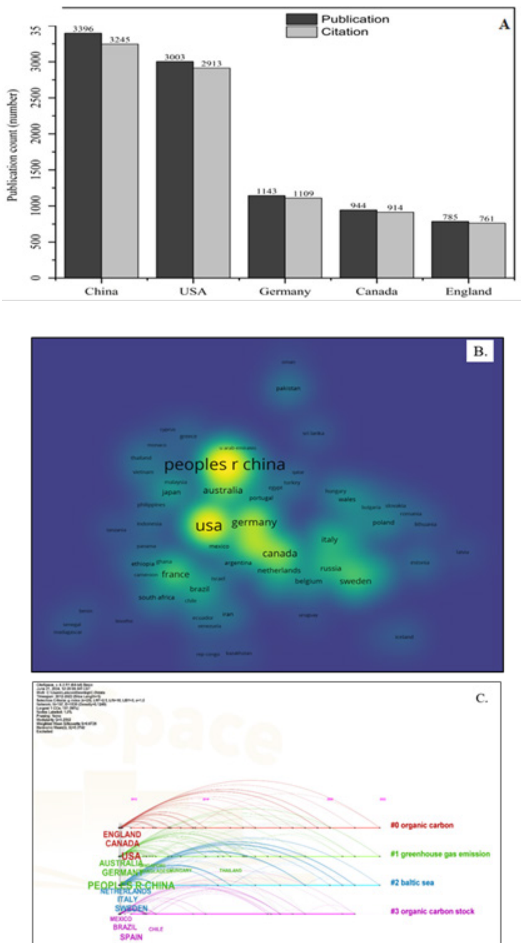

Figure 3 Countries' researched publication, Citation and clustering; (a) Countries publications and citations, (b) Countries clustering in citespace (c) Tree time graph of countries Clusters of countries publication (where N=156, E=1299, Density=0.1074, S=0.68, QS=0.4117).

Research institutions analysis: collaboration and impact

This study examined global research collaboration on organic carbon and climate change among 487 institutions from 2012 to 2022, uncovering a network of 3,169 partnerships (density=0.0288), with 96% of institutions actively engaged in collaboration.[40] The Chinese Academy of Sciences (CAS) led in citations (1,452 citations, Cluster #1: Earth System Models), highlighting its crucial role in foundational climate research (Figure 4a, Table S3). Meanwhile, the University of Quebec stood out as the most influential collaborator (degree centrality=12.88) and showed the strongest citation burst (strength = 13, 2012–2016), emphasizing its leadership in interdisciplinary networks (Table 2). Thematic clusters identified the Qinghai-Tibetan Plateau (Cluster #0) as the most extensively researched area, concentrating on high-altitude carbon dynamics (Figure 4b).[41] Institutions such as INRA (2014–2019) and CSIRO Land & Water (2012–2017) maintained significant 5-year research lifespans, contributing to advancements in soil and water carbon studies. Despite these advancements, notable gaps remain in northern peatland systems, earth system feedback mechanisms, and region-specific impacts (e.g., effects of Arctic warming). Burst analysis indicated temporary leadership from institutions like the University of Alaska Fairbanks (2012–2016, strength=10.01) and Bangor University (2012–2016, strength=7.86), while newer contributors like Iowa State University (2016–2020) indicated shifting research priorities (Table 2, and Table S3). European and Australian institutions (e.g., ETH Zurich, CSIRO) maintained consistent collaboration, while gaps in studies of tropical and boreal ecosystems highlighted the need for greater geographic inclusivity.

The Chinese Academy of Sciences and the University of China Academy of Sciences are renowned for their research on organic carbon and global warming/climate change.[42] However, their citations do not always indicate the quality of their work. The Earth System Model and Qinghai Plateau Cluster are complex systems designed to understand and predict Earth's climate and environment, but they have gaps due to intricacy, sparse observation, changing study priorities, and technical limitations (Figure 4, Table 2).[43,44]

Table 2 Top 10 Institutions with the Strongest Citation Bursts

Institutions	Year	Strength	Begin	End	2012 - 2022
Univ Quebec	2012	13	2012	2016	
INRA	2014	10.31	2014	2019	
Univ Alaska Fairbanks	2012	10.01	2012	2016	
CSIRO Land & Water	2012	7.99	2012	2017	
Bangor Univ	2012	7.86	2012	2016	
CNRS	2013	7.06	2013	2017	
Duke Univ	2012	6.9	2012	2016	
Univ Sydney	2015	6.25	2015	2019	
Univ Lancaster	2012	5.27	2012	2016	
Univ Texas Austin	2013	3.92	2013	2017	
Iowa State Univ	2016	3.58	2016	2020	

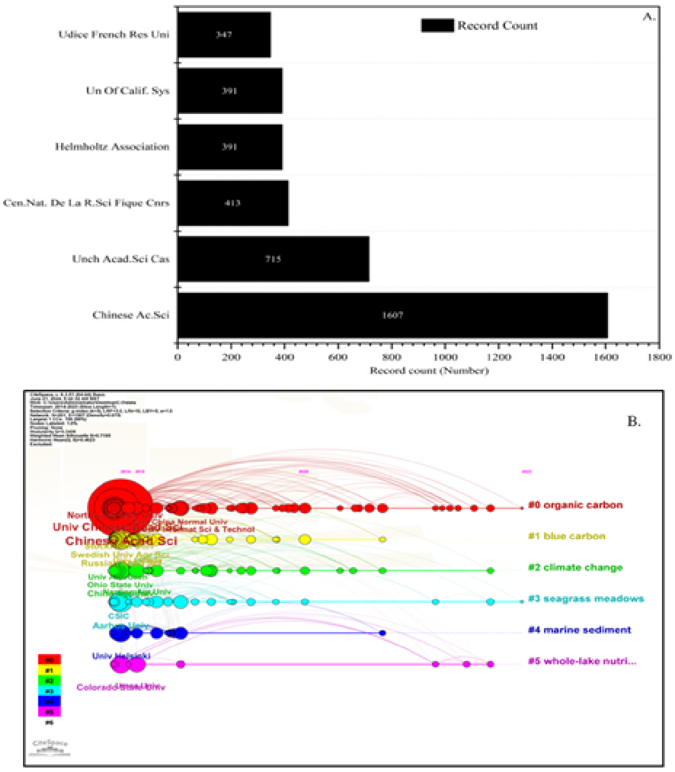

Figure 4 institutes cooperation in study areas A. top 6 Institutes of research record B. cluster of institutes citation and tree cite of institute citation C. link strength and citation count of institutions (N=311, E=1936, Density=0.0402, Q=0.3671, S=0.7044, QS=0.4826).

Author co-citation analysis (ACA)

Indicators of a researcher's research capability, level of cooperation, and academic influence include their publications and collaboration networks.[45] Using "author" as the node type, we obtained a graph of author cooperation relationships with 558 nodes and 990 connections.

The authors' cooperation network graph has a modularity Q score of 0.8377, 54% connections, and a network density of 0.064, indicating low cooperation. The network has several autonomous clusters but no distinct boundaries. Emerging authors like Oscar Serrano and Jin-Sheng He show strong citation bursts, with an average silhouette score of 0.8926. Rattan Lal leads with 78 citations and 30 degrees (Figure 5a). Lal Rattan (2012) and Luo Yiqi have been awarded the most citations and degrees, indicating their significant contributions to the field. The "several viewpoints" approach, using network visualization techniques, helps analyze data structures and linkages in large databases. Understanding the Earth's carbon cycle and its impact on climate change is crucial (Figure 5a, Table 3).[46]

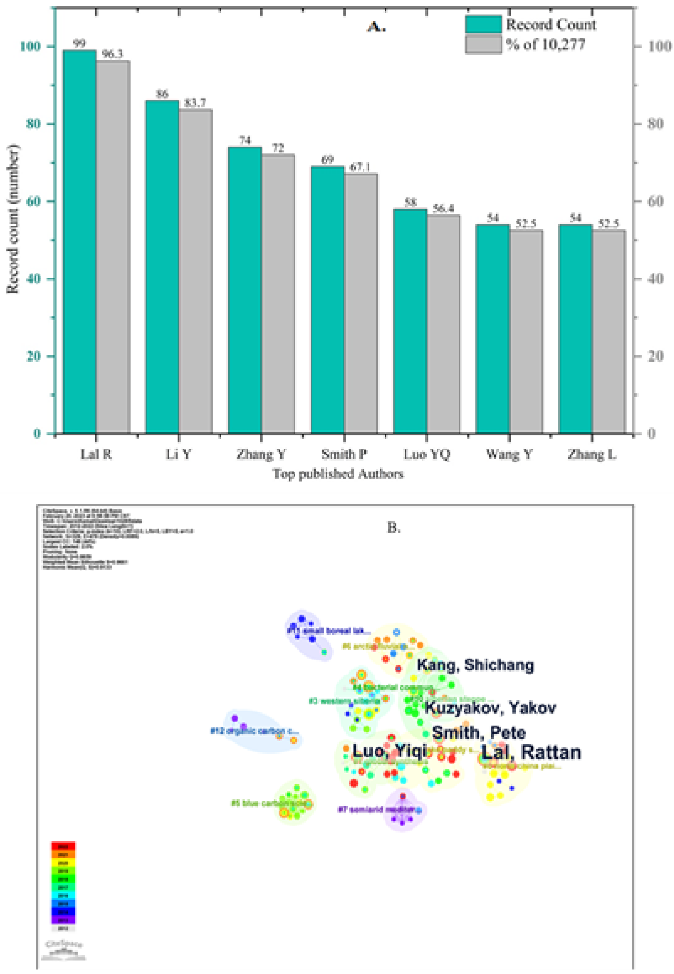

Figure 5 Author Co-Citation Analysis (a) Authors publication in numbers (b) Authors clustering.

Publications with a high degree of betweenness were linked to two or more clusters, and hence to two or more themes (clusters).[47] Connecting themes and synthesizing ideas can transform the way ideas are linked, resulting in a revolutionary relationship (Figure 5b). Author clustering reveals geochemistry, geophysics, and soil science as the most studied areas, with renowned researchers, but gaps exist in environmental science, geoscience, multidisciplinary studies, ecology, green sustainable science, and technology.

Table 3 Authors burst strength and duration time

Authors	Year	Strength	Begin	End	2012 - 2022	Time
Serrano, Oscar	2019	5.36	2019	2022		4
He, Jin-Sheng	2017	5.18	2017	2019		3
Duarte, Carlos M	2017	4.78	2017	2019		3
Bianchi, Thomas S	2012	4.72	2015	2017		3
Laudon, Hjalmar	2012	4.68	2012	2016		5
Guenet, Bertrand	2018	4.33	2018	2020		3
Baldock, Jeff	2014	4.19	2017	2019		3
Aiken, George R	2012	4.03	2012	2016		5
Macdonald, Robie W	2012	4.02	2015	2017		3
Macreadie, Peter I	2015	3.89	2017	2019		3

As previously stated, higher degree values indicated the novelty of publications.[22,47,48] However, Oscar Serrano (2019) ranked first in bursts with 5.36 bursts (2019-2022), followed by Jin-Sheng He (2017) with 5.18 bursts (2017-2019). George R. Aiken (2012) had a burst of 4.03 over a five-year span (2012-2016), indicating the strength of his burst (Table 3).

A study predicts soil respiration rates based on moisture, air temperature, and rainfall, with resin-extractable phosphorus being the most accurate indicator.[49] Forest floor biomass increases soil respiration, indicating microbial deterioration. Retaining soil organic carbon can slow greenhouse gas emissions and global warming. Soil aggregates account for 90% of SOC sequestration. Reducing straw usage increases SOC absorption, decreases carbon mineralization, and increases efficiency (Figure 6, Table S4).[50]

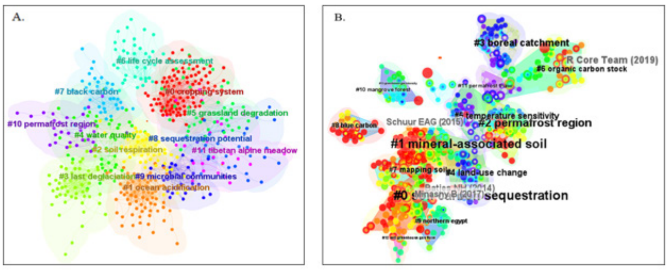

Figure 6 CiteSpace created a cluster view of the document co-citation analysis (DCA) network. A. Cluster of Document Co-Citation Analysis B. Tree time graph of authors. (N=717, E=2312, CC=625(87%), Density=0.009, modularity Q = 0.769; average silhouette = 0.9183, QS=0.8371).

DCA (Document Co-Citation Analysis) references

The Document Co-Citation Analysis (DCA) provides a timeline and cluster view to understand the frequency and amplitude of citation bursts across 56 clusters. The largest clusters are soil carbon sequestration and mineral-associated soil, with a significant module split and decent heterogeneity, indicating high activity levels to the present (Figure 6a). The study emphasizes the need for continued research by highlighting foundational works in the field as well as gaps in smaller clusters, particularly in soil mapping and blue carbon studies.

The most cited reference was R Core Team (2019) with 424 citations, followed by Schuur EAG (2015) with 244 citations, a degree of 48, and a burst strength of 45.12, ranking it highest in both degree and burst metrics (Table 4).[45] Additional analysis of document citations and links revealed that Schuur (2015) had the highest number of citations (1739) and links (40), followed by Minasny (2017) with 857 citations and 43 links, and Stockmann (2013) with 883 citations and 33 links. Other notable documents included Powlson (2014) with 464 citations and 37 links, Scharlemann (2014) with 659 citations and 31 links, and Bradford (2016) with 338 citations and 29 links. Emerging works such as Guenet (2021) and Chenu (2019) also demonstrated significant influence, with 77 citations and 28 links, and 229 citations and 22 links, respectively (Table S5).

The three largest clusters each had an activity span of approximately five years. In contrast, the smaller clusters had lifespans of only 1–4 years. Additionally, the blue carbon and mapping soil clusters started hosting from 2021 onwards. However, the boreal catchment and land use change team identified gaps in their cluster until 2015 (Figure 6b).

Keywords co-citation analysis

CiteSpace's analysis tool uses keywords to identify articles' topics, content, theories, techniques, and perspectives, aiding in subject grouping and understanding distribution, scope, and sub-clustering within research areas through high-frequency keyword extraction, co-occurrence analysis, and term identification.[51,52]

The Web of Science (WoS) data, imported into CiteSpace, consisted of 471 nodes and 28,278 lines, forming a dense network with significant high-frequency keyword nodes. The main research hotspots were identified from keywords, with a focus on the impact of organic carbon on global warming or climate change from 2012 to 2022 (Figure 7a, b).

The most frequently used keywords were climate change, organic carbon, and soil organic carbon (Table S6). The organic carbon export was a highly studied cluster, while the organic carbon stock had a gap in study. The network, composed of eight clusters, displayed keyword bursts, with the most populous term cluster containing 135 members and classified as conservation agriculture, organic carbon, and summer bloom.[53]

The most cited paper was "Global Soil Organic Carbon-Climate Interactions" by Jungkunst (2022) The keyword with the highest burst and size was "carbon budget" for 2014-2018, followed by "long-term experiment" for 2012-2018 (Figure 7a, b).[54]

The highest-population cluster (#0) includes conservation agriculture, organic carbon, and summer bloom. Jungkunst, HF's 2022.0 paper on Global Soil Organic Carbon-Climate Interactions is

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the most referenced. The keyword with the highest burst and largest size is "carbon budget" from 2014-2018 (Table 5).

Table 4 Top 10 References with the strongest citation bursts

References	Year	Strength	Begin	End	2012 - 2022	Degree
Schuur EAG (2015), nature, V520, P171, DOI 10.1038/nature14338, DOI	2015	45.12	2016	2020		48
Hugelius G (2014), biogeosciences, V11, P6573, DOI 10.5194/bg-11-6573-2014, DOI	2014	41.2	2015	2019		39
Batjes NH, (2014) EUR J soil SCI, V65, P10, DOI 10.1111/j.1365-2389.1996.tb01386.x, DOI	2014	34.27	2014	2019		<25
Stockmann U (2013), agr ecosyst environ, v164, P80, DOI 10.1016/j.agee.2012.10.001, DOI	2013	31.11	2014	2018		<25
Paustian K. (2016), nature, V532, P49, DOI 10.1038/nature17174, DOI	2016	25.54	2017	2022		29
Powlson DS. (2011), eur j soil sci, V62, P42, DOI 10.1111/j.1365-2389.2010.01342.x, DOI	2011	25.19	2012	2016		<25
Stocker TF. (2014), CLIMATE CHANGE 2013, V0, PP5, DOI 10.1017/CBO9781107415324.004, DOI	2014	25.06	2015	2019		<25
Powlson DS (2014), nat clim change, V4, P678, DOI 10.1038/nclimate2292, DOI	2014	21.38	2015	2019		<25
Bond TC (2013), J geophys res-atmos, V118, P5380, DOI 10.1002/jgrd.50171, DOI	2013	19.22	2014	2018		<25
Todd-Brown KEO (2013), BIOGEOSCIENCES, V10, P1717, DOI 10.5194/bg-10-1717-2013, DOI	2013	17.35	2014	2018		

Table 5 Sample keyword bursts computed via co-occurring author keywords analysis

Rank	Keywords	Year	Strength	Begin	End	2012 - 2022
1.	Carbon budget	2014	7.85	2014	2018	
2.	Long term experiment	2012	7.39	2012	2018	
3.	Baltic sea	2014	6.59	2014	2018	
4.	Seawater	2012	6.38	2012	2016	
5.	Food web	2012	6.02	2015	2019	
6.	Acidification	2012	5.25	2012	2016	
7.	Benthic foraminifera	2012	5.18	2012	2016	
8.	Water table	2015	5.05	2015	2019	
9.	Bay	2013	4.96	2013	2018	
10.	Nutrient limitation	2015	4.29	2015	2019	

The CiteSpace analysis tool uses keywords to identify article topics, content, ideas, techniques, and points of view on the impact of organic carbon on global warming from 2012 to 2022. It organizes the network into eight clusters, with conservation agriculture, organic carbon, and summer bloom being the most popular (Figure 7).[53]

The research explores the impact of climate change, organic carbon, and soil organic carbon on ecosystems. It uses terms like "climate change," "organic carbon," and "soil organic carbon" to measure carbon dynamics and understand their long-term effects. The focus is on sustainable practices and ecosystem-specific studies. However, gaps in research on organic carbon stocks and environmental variables suggest areas for future exploration.

Climate change and greenhouse gas emission

China and the US, the world's largest carbon dioxide emitters, dominate global research on organic carbon and its relationship to global warming, but their academic impact may be limited by language barriers, uneven access, and research quality.[55,56] Both nations have announced ambitious climate goals: China aims to achieve carbon neutrality by 2060, while the U.S. targets net-zero emissions by 2050. However, the practicality and efficacy of these pledges remain subjects of active research and debate.[57]

Citation trends in climate change research are influenced by factors like journal prestige, author prominence, and policy relevance.[58] China recorded the highest citation counts in 2012, likely due to its substantial research output and global urgency.[59] The U.S. followed closely, with sustained influence and robust research infrastructure. Citation bursts highlight shifting regional priorities, with Bangladesh and England experiencing sudden spikes in citation activity.[60] Rattan Lal and Yiqi Luo emerged as the most frequently cited authors in 2012 and 2015, highlighting their foundational contributions to climate science. Schuur E.A.G. also experienced a sharp rise in citations in 2015.

Soil organic carbon (SOC) retention

Climate change poses significant challenges to soil organic carbon retention, including knowledge gaps in ecosystems, Alaskan Arctic, temperature sensitivity, GHG stabilization, boreal catchments, permafrost region, and mineral-associated soils.[61,62] While rising global temperatures affect major river basins in different ways, the precise impacts remain unclear due to the complexity of these systems.[63] Climate change affects Arctic tundra and boreal forests, but hydrological models underestimate permafrost melting risks. Organic matter lability and temperature sensitivity debate, with chemically resistant carbon potentially more vulnerable.[64,65] Research on greenhouse gas emissions from farming practices, including permafrost regions, is ongoing, with uncertainties surrounding thawing in warming environments and decomposition in fine-textured soils.[62,66]

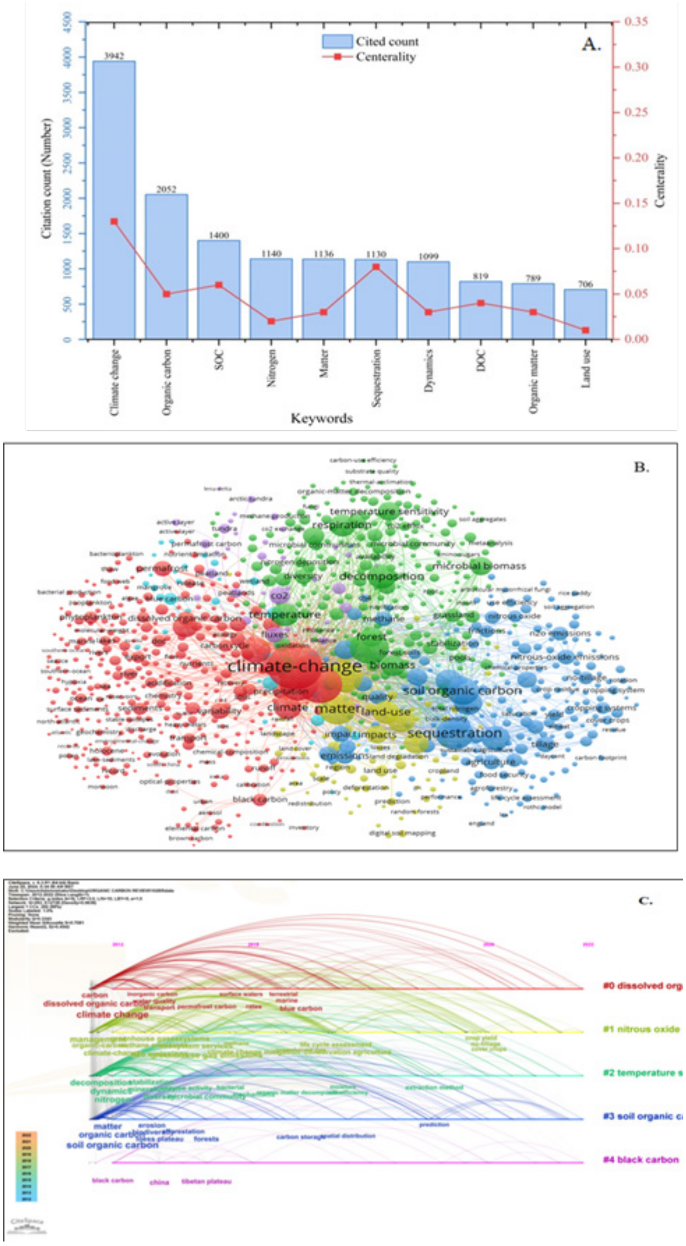

Figure 7 Keywords analysis, (a) Top rank cited keywords of countries publication (b) Tree time graph and Clusters.

Agricultural practices like tillage and crop rotation are causing uncertainty in long-term soil organic carbon storage and greenhouse gas emissions, while mineral-associated soils are under scrutiny due to warming.[67] The carbon release of permafrost thaw is uncertain due to insufficient data on hydrologic changes and microbial activity, necessitating region-specific models, research in less-studied areas, and agricultural innovations.[68] Combining scientific understanding with policy efforts is crucial for mitigating climate risks.

Clustering organic carbon and global warming or climate change

Research has mainly concentrated on mangroves, organic matter, and seagrass meadows because of their crucial roles in carbon sequestration and climate regulation.[69] Mangroves are significant contributors to soil carbon storage and can transfer carbon to nearby ecosystems, including seagrass meadows.[70,71] Seagrass meadows, occupying less than 1% of the ocean's surface, contribute to 10% of annual carbon sequestration, highlighting the importance of organic matter in soil health and ecosystem services.[72] Research on tropical farmland's relationship with Organic Carbon and global warming is limited due to conflicting views on temperature sensitivity and carbon decomposition, and a complete transition could increase net emissions.

Key ecosystems and research gaps identified

Research on OC and its role in combating global warming has mainly focused on mangroves, seagrass meadows, and organic matter. Mangroves are key soil carbon reservoirs, while seagrass meadows contribute to 10% of marine carbon sequestration. Organic matter supports biodiversity and food security while stabilizing carbon stocks. However, uncertainties in OC dynamics, particularly in tropical farmlands and under different environmental conditions, make predictions challenging.

Research gaps was in environmental science, geoscience, multidisciplinary studies, ecology, green sustainable science, and technology are significant, particularly in the context of organic carbon and global warming or climate change.[73,74] Researchers identified key areas for future research, including integrating indigenous and local knowledge, understanding consumption patterns, effective governance systems, and equity in benefit distribution, to address climate change and sustainability challenges.[75] Multidisciplinary approaches are required to address these complex environmental problems, involving the integration of various disciplines including science, engineering, social science, and the humanities.[76]

Knowledge gaps in understanding the impact of organic carbon on climate change include bore lakes, green and black carbon, ocean acidification, microbiological dynamics, and fen peat incubation. These areas require further research to improve our understanding. A global meta-analysis of soil organic carbon in the Anthropocene highlighted neglected ecosystems like wetlands as significant knowledge gaps requiring further research.[77]

Factor of organic carbon and global warming

Green and black carbon

Black carbon, also known as soot, is a small particle discharged into the atmosphere by sources such as diesel engines, coal-fired power plants, and biomass burning.[78,79] It absorbs sunlight and produces heat, similar to CO_2, a major GHG contributing to global warming.[80] Black carbon, despite its short lifespan, significantly contributes to global warming by absorbing solar radiation and generating heat, accelerating Arctic sea ice melting and potentially causing irreversible climate change.[81]

Ocean acidification, a 200-year-old process triggered by the industrial revolution, reduces ocean pH due to CO_2 uptake, impacting ecosystems, food supply, economy, tourism, and recreation.[82,83] Low carbonate ions in oysters and clams hinder calcium carbonate production, causing ocean acidification, damaging estuaries, affecting economies, and affecting nutrition. Mitigation efforts may reverse this process.[84]

Microbiological dynamics

Microbiological dynamics refer to the changes in microbial communities due to environmental changes, and understanding these dynamics is crucial for forecasting the regional carbon cycle in the context of global warming.[85,86] Climate change can affect microbial species distribution, variety, and abundance, potentially altering the trajectory of critical ecosystem processes, including the carbon and nitrogen cycles, which produce climatic gases like CO_2, CH_4, and N_2O.[87,88]

Soil microbial communities have higher-order features due to their interactions, which are not present in individual microorganisms. Changes in the thermal state of the active layer, mostly bound in SOM, also impact the dynamics of soil organic carbon.[89]

Climate change impacts microbial species distribution, abundance, and interactions, affecting their range and ecological contexts. Understanding Microbiological Dynamics and managing SOC is crucial for addressing climate change concerns and enhancing soil fertility.[90]

Fen peat incubation

Fen Peat Incubation is a study that examines the decomposition rates of peat, especially in fen ecosystems, under different climatic conditions.[91] Peatlands, which are major carbon sinks due to their soggy environment, are now becoming carbon sources due to decomposition and burning activities.[92] This transition to renewable energy sources, such as rewetting drained peatlands and sustainable management strategies like paludiculture, is crucial for mitigating global warming.

Effective methods for mitigating greenhouse gas (GHG) emissions

The fight against climate change involves a multifaceted approach that includes reducing fossil fuel emissions, transitioning to cleaner energy sources, and promoting sustainable forest management.[93] Methane emissions are a significant part of human-caused emissions, and strategies like leak detection and repair can reduce them. Decarbonization aims to transition to zero-carbon renewable energy sources.[94] Strategic planning, stakeholder engagement, and policy alignment can accelerate renewable energy transition, with governments and organizations promoting forest conservation through legislation and economic incentives.[95]

Forests act as carbon sinks, absorbing CO_2 from the atmosphere, and sustainable management ensures resources are managed to meet current demands and future generations' needs.[96] CH_4 capture is a crucial strategy for reducing greenhouse gas emissions, with a global warming potential more than 25 times greater than that of CO_2 over a 100-year period.[97] Market-based solutions like carbon credits and emission trading systems can incentivize companies to capture methane, earning credits by reducing emissions.

Climate change strategies include forestation, reforestation, soil carbon sequestration, organic farming, and direct air capture technology to enhance carbon sinks and store CO_2. Solar radiation management and adaptation strategies aim to counteract warming from GHGs through infrastructure construction or retrofitting.[98] Natural solutions involve restoring ecosystems, shifting agricultural practices, water management, and urban planning.

Advancing inclusive and collaborative climate research

Interdisciplinary collaboration

The research emphasizes the vital need of developing solid multidisciplinary alliances to handle complex climate concerns effectively. By incorporating knowledge from multiple domains such as ecology, economics, and technology, academics may build holistic approaches that address the multidimensional character of climate challenges.[99]

Geographic Inclusivity

Currently, European and North American institutions dominate climate research. However, there is an urgent need to widen regional coverage, notably by including tropical and boreal ecosystems into scientific research.[100] These regions play critical roles in global carbon cycles and climate dynamics, yet they are underrepresented in research efforts.

Emerging themes

Recent trends in climate research show a move toward developing subjects including blue carbon, Arctic studies, and conservation agriculture. These domains reflect changing priorities among the scientific community.[101] Future research should focus studying understudied places and including socioeconomic aspects to create a full knowledge of climate impacts and solutions.

Policy implications

The findings highlight the need for scalable policy solutions that match research efforts with global climate resilience goals. Mechanisms such as carbon trading systems and equitable partnerships can aid in the efficient implementation of climate policies while addressing imbalances between governments and communities.[102] Policymakers must prioritize collaboration to ensure that these solutions benefit all stakeholders. By closing research gaps and encouraging collaboration, the scientific community can improve our understanding of organic carbon dynamics. This advancement will lead to the development of effective climate change mitigation techniques, paving the path for a more sustainable future.

Recommendations for future research and policy

Based on the comprehensive bibliometric analysis of global organic carbon research from 2012 to 2022, this study identifies critical gaps and emerging priorities. To bridge these gaps and align scientific efforts with the urgency of the climate crisis, the following recommendations are proposed for researchers, funding bodies, and policymakers:

Prioritize research in underrepresented ecosystems and regions

Focus on Vulnerable Carbon Sinks: Intensify research efforts in critical but understudied ecosystems, particularly northern peatlands, tropical forests, and coastal blue carbon ecosystems (mangroves, seagrasses, salt marshes) in the Global South. These regions are vital carbon sinks but are highly vulnerable to land-use change and climate impacts, as indicated by the clustering gaps in our analysis.

Address Geographic Imbalances: Actively promote and fund research led by institutions in the Global South (e.g., Bangladesh, Ethiopia, Nepal) to ensure context-specific solutions and equitable knowledge production. International grants should mandate equitable partnerships and capacity building, moving beyond the current dominance of China, the US, and European nations.

Foster interdisciplinary and transdisciplinary collaboration

Integrate Socioeconomic and Biophysical Sciences: Move beyond siloed environmental science by integrating economics, social sciences, and political science into OC research. This is essential for designing feasible carbon sequestration projects, understanding adoption barriers by farmers, and developing equitable carbon trading mechanisms. Strengthen Data and Model Integration: Encourage collaboration between field scientists, remote sensing experts, and modelers to improve the representation of complex OC dynamics (e.g., permafrost thaw, microbial processes) in Earth System Models, reducing uncertainties in climate projections highlighted in our document co-citation analysis.

Scale Up and deploy promising mitigation strategies

Accelerate Biochar Application: Support large-scale, long-term field trials to quantify the carbon sequestration potential and co-benefits (e.g., soil fertility, crop yield) of biochar across different soil types and agricultural systems. Develop cost-effective production technologies to enhance scalability. Incentivize Blue Carbon Conservation and Restoration: Implement policies that create financial incentives, such as verified carbon credits, for the protection and restoration of mangrove forests, seagrass meadows, and tidal marshes. Invest in mapping these ecosystems to accurately quantify their carbon stocks, addressing the research gaps identified in the keyword and cluster analysis.

Enhance policy-research alignment and knowledge transfer

Develop Robust Carbon Accounting Frameworks: Support research that improves the monitoring, reporting, and verification (MRV) of soil carbon stocks to underpin transparent and trustworthy carbon trading systems. Translate Research into Actionable Policy: Establish science-policy interfaces to ensure that the latest research on SOC management, sustainable agriculture, and nature-based solutions directly informs national climate action plans (NDCs) and land-use policies. Promote Knowledge Exchange: Create platforms for sharing best practices and research findings between leading research nations (e.g., China, USA, EU) and climate-vulnerable countries to foster global learning and implementation.

Target specific knowledge gaps through directed funding

Investigate Black Carbon and Ocean Interactions: Increase research on the role of black carbon in the carbon cycle and its impact on albedo, as well as the interactions between ocean acidification and marine carbon pumps. Elucidate Microbial Dynamics: Fund research to better understand how climate change alters soil microbial communities and their function in carbon mineralization and stabilization, which is critical for predicting carbon-climate feedbacks. Understand the Fate of Thawing Permafrost Carbon: Prioritize studies on the biogeochemistry of fen peat incubation and the hydrological controls on greenhouse gas emissions from thawing permafrost. By implementing these recommendations, the global scientific and policy community can transform the insights from a decade of OC research into tangible, effective, and equitable actions. This will be paramount for protecting existing carbon sinks, enhancing carbon sequestration, and ultimately achieving the goals of the Paris Agreement.

Summary

This decade-long bibliometric analysis of organic carbon (OC) research charts the field's evolution from foundational soil science to emerging frontiers in blue carbon and permafrost feedbacks, underscoring OC's central role in climate mitigation. While China and the U.S. lead in publication volume, the analysis reveals that strategic international collaboration, exemplified by nations like Denmark, is the true multiplier of research impact. Critically, the study identifies not just geographical imbalances but fundamental knowledge gaps in key ecosystems—such as northern peatlands and tropical farmlands—and a persistent socio-technical divide. The robust understanding of biophysical solutions like biochar is starkly contrasted by a lack of research on the socioeconomic barriers to their implementation. Therefore, bridging this gap and addressing these blind spots through inclusive, transdisciplinary collaboration is the imperative next step to translate a decade of research into equitable and effective climate action aligned with the 1.5°C target.

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Data availability statement

The datasets generated during and/or analyzed during the current study are available upon request.

Competing interests and declarations

The authors have no conflicts of interest. All named authors have approved the manuscript. The order of authorship has been confirmed. The Corresponding Author is the sole contact for the editorial process, and no funds have been allocated for publication.

Author's contribution

I. Kemal Adem Abdela:- Conceptualization, Software handling, Visualization, Data Curation, Writing original draft.

II. Abdisa Abebe Gerbi, Conceptualization, Software handling, Visualization, Data Curation, reviewing.

III. Endris Ali Mohammed: - Methodology, Formal analysis, Reviewing.

IV. Bekalu Melis Alehegn- Methodology, Formal analysis, Reviewing

V. Dereba Megersa:- Methodology, Editing.

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