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Scientific advances and future trends in ocean carbon sink: an interdisciplinary review

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Ocean carbon sink is an emerging and interdisciplinary research area that plays a vital role in the global carbon cycle. This paper reviews recent scientific advancements in ocean carbon sink research, focusing on the mechanisms for capturing, utilizing, and sequestering atmospheric CO₂, and highlights its contribution to climate change mitigation and adaptation. Using bibliometric analysis based on CiteSpace and data from the Web of Science and Scopus, we examine research hotspots and topic evolution through country collaboration, journal co-citation, and keyword co-occurrence networks. The findings show that ocean carbon sink research is shaped by complex scientific uncertainties and the integration of multiple disciplines. Current research hotspots include scientific advances, technological innovation, and governance challenges related to sustainable development. In general, recent studies emphasize the role of carbon sink, the value of nature, and the importance of precautionary management. This paper underlines the need for coordination between scientific and social dimensions of carbon sink functions, and it draws attention to the ethical aspects of carbon sink governance. It advocates for multi-stakeholder participation, precautionary governance, and policy-based financial system to support climate resilience and foster the sustainable development of the oceans.

KEYWORDS

ocean carbon sink, scientific advances, bibliometric analysis, climate change, sustainable development

1 Introduction

The oceans represent a vast and dynamic long-term carbon sink within the global carbon cycle (Nellemann et al., 2009; Liu and Tang, 2013). The oceans capture, utilize, and sequester atmospheric CO₂, facilitating the carbon cycle among the atmosphere, terrestrial systems, and marine environments (IPCC, 2013; Li et al., 2018; Deng et al., 2024).

Compared to terrestrial carbon sinks, the ocean carbon sink (OCS) is generally more stable and is expected to play a central role as the dominant natural carbon sink in the future (Yang et al., 2023; Silvy et al., 2024). However, the capacity of carbon sinks—particularly the OCS—is subject to considerable uncertainty. The ocean's ability to sequester carbon is influenced by multiple environmental factors, including sea surface temperature, wind speed, ocean circulation, and biological productivity. It is highly sensitive to climate change and susceptible to natural disturbances such as volcanic eruptions, which could accelerate the saturation of the ocean's carbon uptake capacity (Frölicher et al., 2011; DeVries et al., 2019). A decline in ocean carbon sequestration would leave more CO₂ in the atmosphere, further intensifying global warming trends (Friedlingstein et al., 2023).

In light of the prevailing scientific consensus that climate warming is primarily caused by CO₂ emissions (Jiang et al., 2022), the international community has acknowledged the significant potential of the oceans to mitigate and adapt to global climate change. Academic research is increasingly focusing on the important role of marine ecosystems as sinks and reservoirs of greenhouse gases. Much of the historical knowledge on OCS is related to modeling, involves simulating regional or global ocean circulation to assess ocean carbon concentrations and the interdecadal variability of the OCS. These studies are used to analyze the interactions between the oceans and climate change (Aumont et al., 2015; Frölicher et al., 2015; Resplandy et al., 2015; Breeden and McKinley, 2016; Boucher et al., 2020; Li et al., 2022a; Bellenger et al., 2023; Rodgers et al., 2023). With the wide coverage of the oceans, data sparsity remains a fundamental limitation in quantifying OCS, and the importance of satellite observations for assessing OCS is mentioned in the relevant literature (Gloege et al., 2021), thus providing more data to support the understanding of the changes in OCS.

In addition to analyzing the evolutionary trend of OCS through modeling, related literature also explores the role of ocean organisms in the carbon cycle, accounting of OCS, and carbon sink market trading (Sondak et al., 2017; Liu et al., 2019, 2022; Zhao et al., 2021; Li et al., 2022b; Wu et al., 2023; Wei et al., 2024; Zhang et al., 2024b). The concept of blue carbon appears frequently in these discussions (Atwood et al., 2015; Lin, 2019; Lovelock and Duarte, 2019; Howard et al., 2023; Sidik et al., 2023), yet there is some confusion in current research on the concepts of OCS and blue carbon. Some literature directly equates both (Feng et al., 2021; Liu et al., 2022a; Yu et al., 2023; Zhang et al., 2024b), while others distinguish between coastal blue carbon and open ocean carbon sinks (Laruelle et al., 2018; Mathis et al., 2022). The concept of blue carbon, as initially introduced in the 2009 publication *Blue Carbon: The Role of Healthy Oceans in Binding Carbon*, has garnered significant academic attention. This seminal work not only conceptualized the notion of blue carbon but also explicitly emphasized the biological carbon captured by marine living organisms (Christianson et al., 2022; Murphy et al., 2023; Powers et al., 2025). Notably, it particularly highlighted the carbon sequestration capacity of the three predominant coastal ecosystems. Subsequent research has largely aligned with this perspective, underscoring the notion that blue carbon is a critical component of the marine carbon

cycle (Nellemann et al., 2009; Contreras and Thomas, 2019; Lovelock and Duarte, 2019; Christianson et al., 2022). The management of blue carbon is currently dominated by terrestrial-based methodologies and strategies. This approach facilitates the quantification of carbon sequestration stocks (O'Connor et al., 2020), thereby enhancing the feasibility of implementing conservation or restoration actions aimed at directly influencing the carbon sequestration potential of these ecosystems (Macreadie et al., 2017; Howard et al., 2023). OCS is based on “carbon sequestration processes” and covers all aspects of ocean carbon cycle, not just a certain type of ecosystem (Macovei et al., 2020; Grégoire et al., 2021; Wang et al., 2024a). In addition to the biological process of photosynthesis through which vegetation sequesters CO₂, the OCS encompasses the physical process of seawater circulation and the chemical process through which seawater reacts with CO₂ (McKinley et al., 2017; Macovei et al., 2020). Since most OCS processes are relatively difficult to contain and control (Oschlies et al., 2025), the governance of OCS focuses on geomorphology-based technological innovation. This indirectly enhances the ocean's carbon sequestration capacity through technical intervention (Röschel and Neumann, 2023; Wei et al., 2024). Overall, blue carbon is a functional concept while OCS is a scientific concept, and blue carbon ecosystems are part of the OCS cycle.

Research on OCS spans a wide range of disciplines, including but certainly not limited to marine ecology, biogeochemistry, geology, oceanography, law and economics, reflecting its interdisciplinary nature (Jiao et al., 2016). Moreover, a comprehensive understanding of the OCS necessitates an examination of the interplay between natural and social sciences. At present, research related to OCS is predominantly situated in the natural sciences and is primarily grounded in technical interpretations. Research on OCS in the social sciences and policy has remained relatively limited, while it has undergone steady and increasingly noticeable growth in recent years.

Therefore, based on the scientific topic of OCS, this paper conducts a bibliometric analysis with the help of CiteSpace to evaluate the research topics and evolutionary trends of OCS. It is imperative to note that this provides the foundation for a systematic review of contemporary scientific advancements in OCS literature. This approach enables an assessment of significant risks and facilitates an expansion of research on carbon sink policy, which is crucial for enhancing the policy's social and ethical dimensions. We emphasize an effective and adaptive governance framework that considers the scientific, economic, and social measures that may be needed to provide recommendations for future research advances in OCS to restore the ocean's capacity for emission reduction, sink enhancement, and long-term sustainable development.

2 Materials and methods

2.1 Materials

In this study, research related to OCS is searched and collected through the Web of Science (WoS) and Scopus databases. WoS and Scopus are very influential sources of journal citation data (Pranckutė,

2021). The WoS Core Collection covers high-quality journals, books, and conference proceedings in the natural sciences, social sciences, and arts and humanities, and is widely used with an overall balanced structure of literature within the database (Birkle et al., 2020; Singh et al., 2021). Scopus, on the other hand, has only a single citation index and has higher coverage of the social sciences than WoS, with a better representation of journals from all regions of the world (Asubiaro et al., 2024; Tasneem and Ahsan, 2024). Therefore, this paper synthesizes these two databases for bibliometric analysis to capture the diversity of interdisciplinary literature searches on OCS, thereby ensuring the comprehensiveness of data analysis.

2.2 Research methods

In view of the significant role of peer review in safeguarding academic quality in journal articles (Tennant and Ross-Hellauer, 2020), only research articles and review articles are considered in this paper. The main content of this study is the scientific advances of OCS with the search ending on December 31, 2024. The search equation for WoS in this paper is TS=((ocean* carbon sink*) OR (marine carbon sink*) OR (ocean* carbon sequestration*) OR (marine carbon sequestration*) OR (ocean* CO₂ sequestration*) OR (marine CO₂ sequestration*) OR (ocean-based carbon dioxide removal) OR (ocean-based carbon dioxide sequestration*) OR (blue carbon)) AND TS=((scientific progress*) OR (scientific advancement*) OR (technological progress*) OR (technological advancement*) OR ((technical progress*) OR (technical advancement*) OR (innovation*))) AND DT= (Article or Review Article) AND Time span=(NOT 2025). There are 262 search results. After de-duplication and screening of irrelevant publications, 131 usable publications remain. The search formula of Scopus is TITLE-ABS-KEY ((ocean* AND carbon AND sink*) OR (marine AND carbon AND sink*) OR (ocean* AND carbon AND sequestration*) OR (marine AND carbon AND sequestration*) OR (ocean* AND CO₂ AND sequestration*) OR (marine AND CO₂ AND sequestration*) OR (ocean-based AND carbon AND dioxide AND removal) OR (ocean-based AND carbon AND dioxide AND sequestration*) OR (blue AND carbon)) AND TITLE-ABS-KEY ((scientific AND progress*) OR (scientific AND advancement*) OR (technological AND progress*) OR (technological AND advancement*) OR (technical AND progress*) OR (technical AND advancement*) OR (innovation*)) AND (EXCLUDE (PUBYEAR, 2025)) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re")). There are 214 search results. Due to the high degree of overlap between WoS and Scopus, after removing overlapping publications with WoS and filtering out irrelevant ones, 30 new publications are obtained (Figure 1).

Therefore, we integrated the Scopus dataset with the WoS dataset to facilitate comprehensive bibliometric analysis, with a final sample of 161 publications subjected to bibliometric analysis in this paper. Significantly, the sample size demonstrates sufficient statistical power to validate the novel research objective of

synthesizing interdisciplinary scientific progress in OCS. CiteSpace is a Java-based application for interactive and exploratory analysis of the evolution of a single domain to multiple linked domains (Chen, 2018). It is particularly effective in detecting and visualizing key points and emerging trends in scientific publications, as well as the evaluation of potential biases (Chen, 2006; Fang et al., 2018).

3 Bibliometric results

Network analysis through bibliometric tools is very effective in identifying established and emerging areas (Fahimnia et al., 2015). We visualize and analyze the final exported 161 publications through CiteSpace to summarize the evolution of scientific advances in OCS. Studies in disciplines such as materials science and biological sciences—including nanoscience, green energy, biochar, food science and technology, and optics—were excluded from the review due to their lack of relevance to marine-related themes. The exclusion of these studies is unlikely to introduce significant bias.

The CiteSpace parameters were set to a 1-year time slice and a k-value of 25, which defines the scope of influential nodes included in the analysis, enabling the generation of all visual maps and analytical tables employed in this research. Additionally, the merged network pruning algorithm was applied to filter out less significant nodes, thereby enhancing the structural clarity of the research network.

3.1 Exploring research landscape

Time series, which are measurements of a quantity taken over time, are fundamental data objects studied across the scientific disciplines (Fulcher et al., 2013). Furthermore, the number of published papers stands as an important indicator for evaluating the level of discipline development (Xiang and Cao, 2024). Therefore, this section analyzes the final derived publication as a whole based on the time series, which helps to predict the future development of scientific research on OCS. Overall, the number of publications on scientific advances of OCS shows an upward trend, which is divided into three main stages in Figure 2.

Stage I: 1994–2007. There were few publications on scientific advances in OCS, and the publications are not specific to OCS, but rather focus on the oceans' uptake of atmospheric CO₂ incidentally in the context of exploring climate change issues (Lempert et al., 1994; Retallack, 2002), which addresses some elements of the current concept of OCS, such as coastal wetlands (Pant et al., 2003). At this stage, although the international community has recognized the function of the oceans in capturing, utilizing and sequestering CO₂, systematic discussions on this topic remain scarce, and the research contribution to the scientific advance of OCS has been very limited.

Stage II: 2008–2019. Publications on scientific advances in OCS have shown an upward trend from 2008 to 2019, but the increase

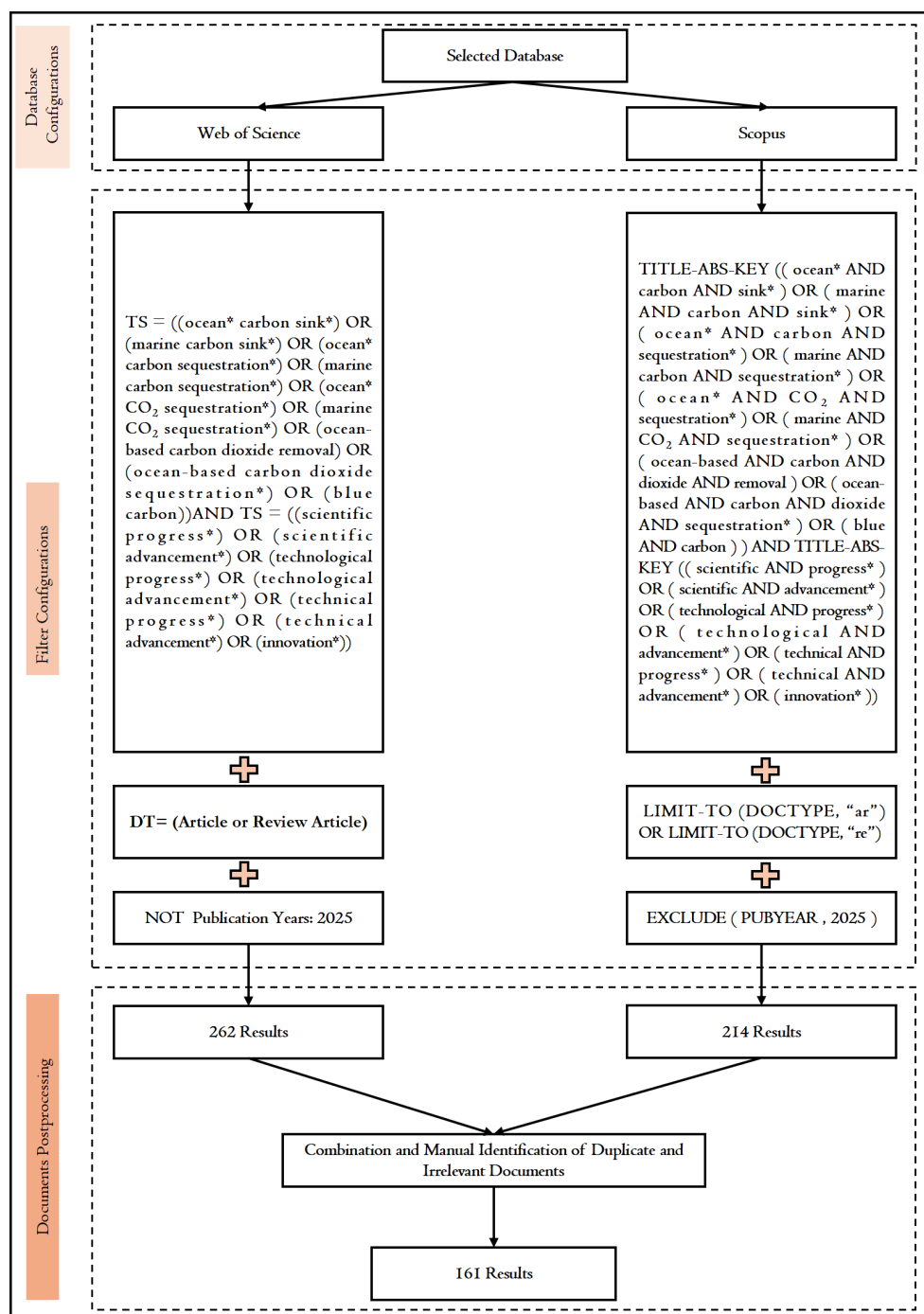


FIGURE 1
Systematic publications selection flowchart.

has been modest and has experienced periodic declines over the period. In fact, since the concept of blue carbon was put forward in 2009, ocean carbon sequestration and its function in responding to global climate change have received widespread attention from the international community. Publications about the function of ocean carbon pools, blue carbon, ocean observation technologies, and social issues related to ocean carbon sequestration have begun to appear, drawing attention to the holistic nature of land and sea

(Dickey et al., 2009; Hansell et al., 2009; Galvez and Gaillardet, 2012; Thomas, 2014; Pan et al., 2016; Jacotot et al., 2018). During this period, the function of the ocean in mitigating and adapting to climate change has been incorporated into more international documents and policies. *The 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* specifically mentioned the function of marine sediments in absorbing CO₂ (IPCC, 2014). The 2015 United Nations Climate

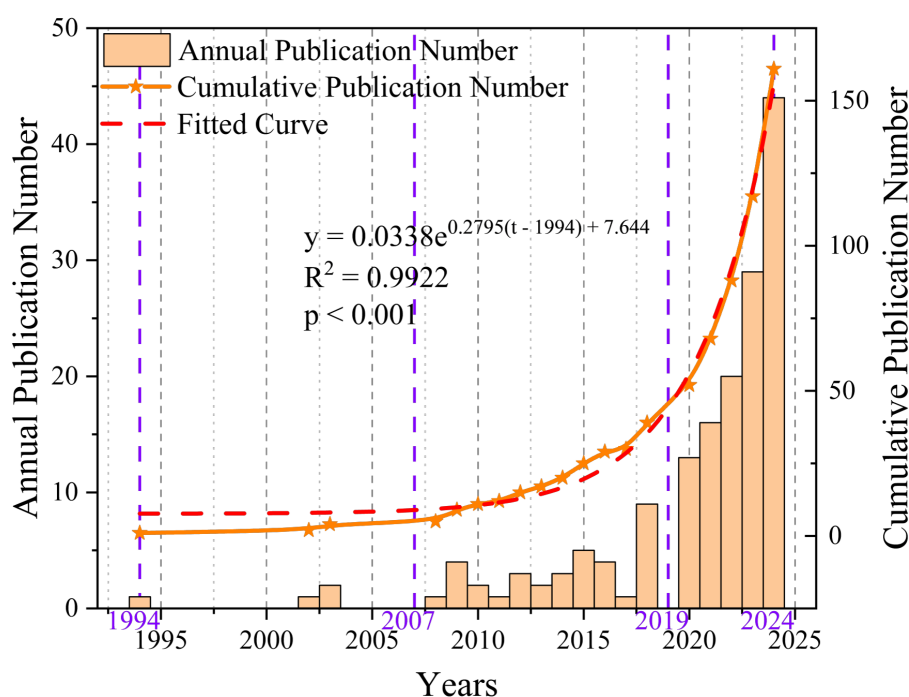


FIGURE 2
Annual trends in publication numbers from 1994 to 2025.

Change Conference (COP 21) formally recognized the critical role of oceans in sequestering carbon, and the *Paris Agreement* made it clear that protecting marine ecosystems contributes to climate justice (UNFCCC, 2015). Overall, these publications are more voluminous than Stage I, showing a significant increase but with repeated fluctuations, which can be explained to some extent by the lag between the timing of scientific research on OCS and the emergence of their publications (Duarte De Paula Costa and Macreadie, 2022).

Stage III: 2020–2024. The number of publications is significantly higher than in the previous two stages, and the growth trend is obvious. Research has become more comprehensive, including diversification of methods and equipment for exploring the oceans, technological developments in carbon capture, utilization, and sequestration, and the climate-ocean prediction models (Schweitzer et al., 2021; Kumar and Sangwai, 2023; Jiang et al., 2024; Lin et al., 2024; Shutler et al., 2024). The scientific correlations between the atmosphere, the oceans and biodiversity have been studied more extensively (Timmermans and Daniel Kissling, 2023). In addition, more attention has been paid to the social functions of OCS in promoting the blue economy, carbon neutrality, and the realization of an ecological civilization and sustainable development of the oceans (Xie et al., 2022; Chen et al., 2024; De et al., 2024). Overall, the potential of OCS has been tapped, and it will continue to develop in the future.

3.2 Analyzing global cooperation networks in research

3.2.1 Global cooperation analysis of national research

Generally speaking, two authors from different countries or regions appearing in the same article are considered to be collaborating. National cooperation network is mapped based on the collaborations between countries in the relevant literature. By analyzing inter-country collaborations, it is possible to identify key countries with a high number of published papers and a high impact on the relevant field (Que et al., 2024). This allows for the determination of which countries and regions are currently more advanced and have made substantial contributions to OCS research. We use CiteSpace to analyze the authors' nationalities of 161 publications. Each node symbolizes a country, with the size of the node corresponding to the volume of published papers. With the threshold set to 5 and authorship conventions taken into account, regional nodes (e.g., Scotland, Wales) were consolidated into their respective national nodes (e.g., the United Kingdom), resulting in 19 nations being displayed in Figure 3. China, the United States, the United Kingdom, Germany, Australia, France, Italy, India, among others, with relatively high scientific and technological levels, have published more scientific research related to OCS. Some nodes are encircled by a purple outer ring, which signifies greater centrality.

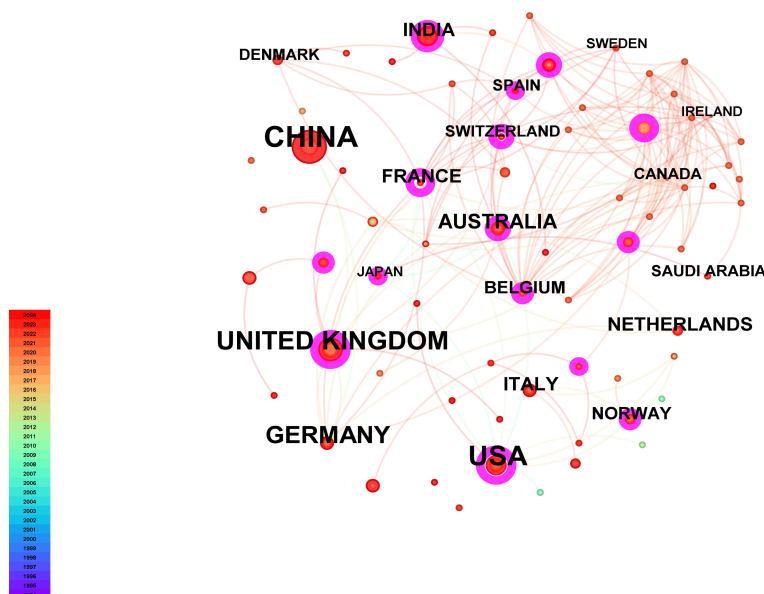


FIGURE 3
Cooperation networks between countries.

The higher the betweenness centrality of a node, the more influential it is within the network (Freeman, 1978; Brandes, 2001). As demonstrated by the high betweenness centrality exhibited by countries such as Switzerland, Belgium and Austria, despite their relatively small number of published articles, the scientific research on OCS carried out in these nations wields considerable influence within the overall network. As shown in Figure 3, the research and participation in cutting-edge science and technology of OCS in Europe and the United States are still at a high level, maintaining direct or indirect cooperation relationships with numerous countries. This indicates that major countries in the Global North continue to dominate scientific research on OCS, while most countries in the Global South still have knowledge gaps in this field. This phenomenon is largely due to the instrumental nature of science and the fact that technological change is a multi-level process that unfolds unevenly over time and space (Voulvoulis and Burgman, 2019). OCS's technology research and development requires substantial investment and human capital advantages, which are closely linked to a country's economic development (Gruber et al., 2023; Sheehy et al., 2024; Xiang and Cao, 2024). This means that future OCS development will still rely on international cooperation, primarily from developed countries in the Global North and some international non-governmental organizations. This cooperation will enhance the capacity of developing countries for OCS research and utilization through funding, technical training, and technology transfer (Thomas, 2014; Reiter et al., 2021; Dobush et al., 2022; Quevedo et al., 2023; Zou et al., 2023).

3.2.2 Journal co-citation analysis

Journals play a crucial role in the dissemination of specialized academic knowledge, and co-citations between journals indicate a

connection between the positioning of the journals, their target scope, and their preferred discipline (Jia et al., 2019). CiteSpace generated a total of 544 nodes. Considering the diversity of journals involved, the threshold was elevated to 41 to ensure the visibility of key citation patterns and to highlight representative periods marked by high citation frequencies (Figure 4). The journals with the highest citation frequencies are Science, Nature, Proceedings of the National Academy of Sciences of the United States of America, Nature Geoscience, PLOS One, Nature Climate Change, Journal of Cleaner Production, Nature Communications, and Energy. As indicated in Table 1, journals with high citation counts are all from scientific fields, including environmental science, biochemistry, oceanography, and energy science. Among them, Nature and Science have the highest citation frequencies, and both journals and their authors exert extensive influence (Garfield, 2006), making them key platforms for researching scientific advancements in OCS. Although journals such as Proceedings of the National Academy of Sciences of the United States of America, PLOS One, Journal of Cleaner Production, and Energy have relatively lower impact factors, they still complement OCS research from diverse disciplinary perspectives.

The co-citations in Figure 4 show that scientific advances in OCS are closely related to the exploration of contents such as climate change, environmental resources, and biodiversity. This thoroughly substantiates the scientific essence and interdisciplinary expanse of OCS. According to the category information of WoS, the basic theories and knowledge of scientific advances in OCS primarily originate from natural sciences. Research on the policies and economic impacts of OCS remains limited within the social sciences. Nonetheless, there has been an upward trend in related research in recent years, with an increasing number of interdisciplinary studies. In the future, global cooperation on

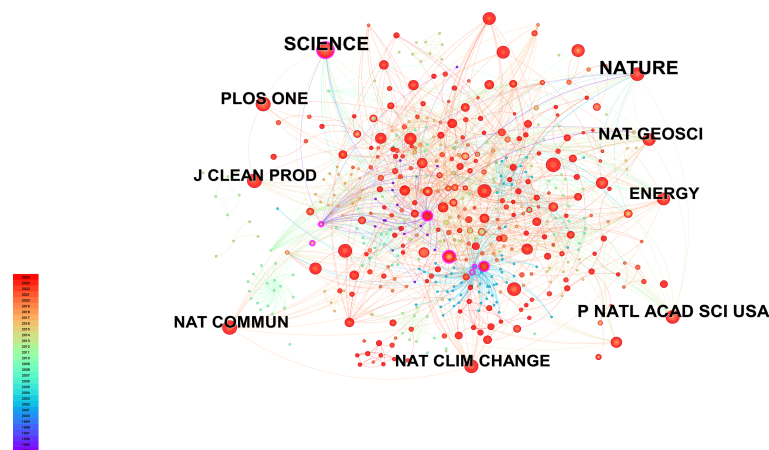


FIGURE 4
Cooperation networks between citation journals.

scientific research related to OCS should integrate multiple technologies. Combining environmental science and social governance collaboration can unlock the OCS's potential. Therefore, cooperation and integration between disciplines must be strengthened.

3.3 Keyword co-occurrence analysis

Among all the bibliometric techniques, keyword co-occurrence analysis is a core perspective for studying cutting-edge developments in related fields. Since keywords are highly summarized words extracted by the authors from the articles, they reveal the research preferences. Visual analysis of these keywords can explore the research co-occurrence of different articles and reduce the judgmental bias caused by subjective factors (Peters and Van Raan, 1993; Wang et al., 2024a). Based on the original software settings, the node type was set to "Keyword" and the threshold to 5, enabling the generation of the co-citation network (Figure 5). It reveals a significant connection between OCS and climate change, as evidenced by the high frequency and betweenness centrality of keywords such as climate change, blue carbon, carbon sequestration, CO₂, and organic carbon. This indicates that there is a close interaction between the carbon sink function of the ocean and climate change.

3.3.1 Keyword clustering analysis

Cluster analysis stands as a pivotal task in contemporary data analysis. It involves assigning a set of objects to distinct groups, also known as classes or categories, in such a way that the objects within the same cluster exhibit greater similarity to each other (based on a predefined property) than to those in other clusters (Emmons et al., 2016; Batool and Hennig, 2021). Nodes with strong connections are grouped, while those with weak connections are placed in separate clusters. Potential cluster labels are chosen from noun phrases and index terms in the cited articles of each cluster (Chen et al., 2010). The cluster labels obtained by Log-Likelihood Ratio (LLR) can

better summarize the attributes of the cluster, and the top clusters are selected according to this algorithm in Figure 6.

According to the clustering information in Table 2, the current scientific research on OCS is primarily categorized into the following aspects: the first category is the social value of OCS, mainly focusing on the interactions between carbon sinks, economic growth and energy. In practice, it synergizes with terrestrial governance, thereby facilitating the realization of sustainable development. This category includes clusters #0, #1, #4, and #8. The second category is the ecological value of OCS, where seawater and marine organisms play important roles in sequestering CO₂, mitigating and adapting to climate change. This category includes clusters #2, #3, #5, and #7. The third category is the scientific value of OCS, which involves the development of ocean technologies such as sensors and testbed mooring sites, as well as their utility in observing and evaluating OCS. This category corresponds primarily to cluster #6. In Table 3, the keywords with the highest citation frequencies—"climate change", "blue carbon", "carbon dioxide", "carbon", "organic carbon", "carbon sink", and "carbon capture"—indicate that the ecological value of OCS remains a core issue in current research.

3.3.2 Keyword burst analysis

Burst detection is a computational technique for identifying mutations in the subject features of certain information or documents (Jon, 2003; Zhou et al., 2018). Burst keywords denote the phenomenon of keywords to be examined jumping over a short period, namely, research frontiers and hotspots at a specific time (Wang et al., 2018). In this research, 11 emerging keywords are shown after setting the γ value to 0.4 in Figure 7. The concepts of "carbon dioxide" and "carbon sink" emerged in 2002 and 2008, respectively, and have remained central to scientific inquiry ever since. They are poised to continue as key research hotspots well into the future. The keyword with the strongest emergence is "carbon sequestration". The longest duration is "ecosystem services" (7 years), which indicates that ocean storage of CO₂ is an important issue for relevant scientific research, and the international

TABLE 1 Top cited journals.

Cited journal	Count	Centrality	Year	Impact factor
NATURE	83	0.06	1994	50.5
SCIENCE	83	0.16	1994	44.8
P NATL ACAD SCI USA	54	0.02	2009	9.4
NAT GEOSCI	50	0.08	2011	15.7
PLOS ONE	48	0.07	2014	2.9
J CLEAN PROD	45	0.02	2016	9.8
NAT CLIM CHANGE	45	0.01	2018	30.3
NAT COMMUN	44	0.00	2018	14.7
ENERGY	42	0.07	2008	9

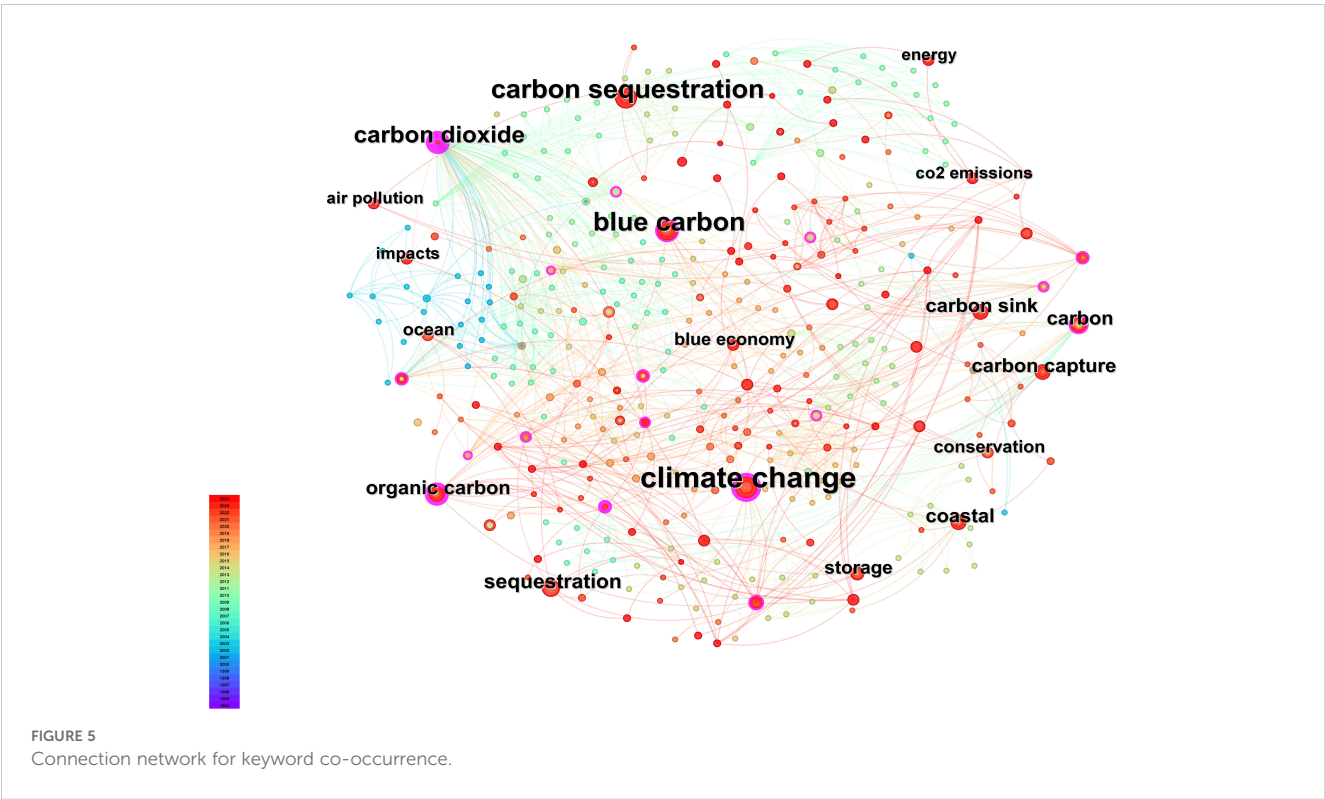
community continues to pay attention to the important role of OCS in regulating the global ecosystem. Accordingly, the scientific realization of the potential of OCS requires an ecosystem-based approach to conservation.

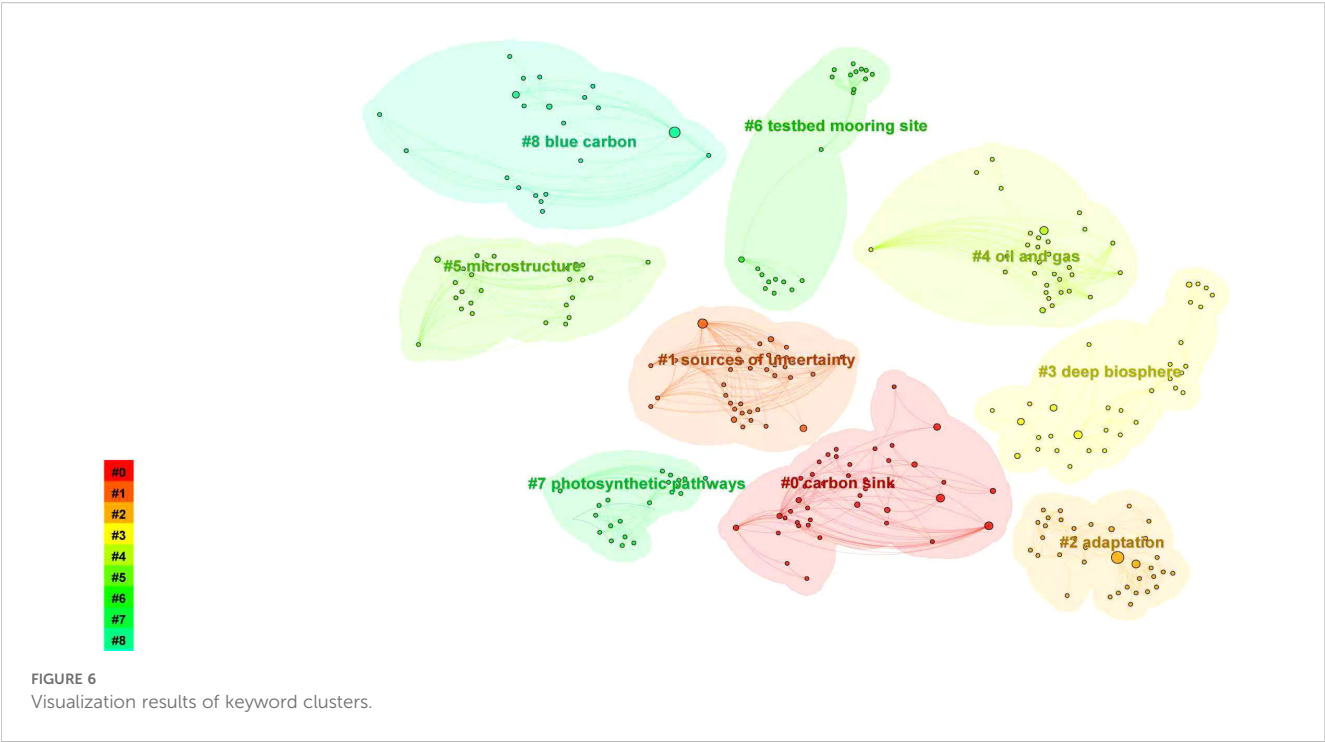
Ocean acidification, a significant adverse effect of climate change, has to some extent exhibited a positive effect in enhancing OCS. Consequently, it has maintained its visibility to the present time, even following the research peak observed between 2014 and 2016. Moreover, “organic carbon” and “air pollution” have recently emerged as prominent keywords. The mounting emphasis on the function of organic carbon in carbon sequestration has elicited considerable interest, thereby propelling research endeavors concerning the fundamental mechanisms of the oceanic biological pump and fostering a more profound

comprehension of the physical and carbonate pumps. Meanwhile, the question of whether CO₂ is a pollutant has gradually developed into a topic of scientific research. The direction of OCS is becoming more and more diversified.

4 Main finding

Bibliometric analysis provides quantitative measurement of various indicators. Within this quantitative framework, qualitative methods, especially the close textual reading, enable deeper theoretical inquiry and contribute to a more holistic understanding of the scientific research landscape (Salmi, 2024). A thorough analysis of the knowledge graph generated by





CiteSpace, as previously described, reveals that extant research on scientific advances in OCS spans a broad range of disciplines, underscoring the necessity for interdisciplinary research approaches (Chen et al., 2024). The inherent complexity of OCS renders it impossible for a single discipline to adequately address its core issues. The natural sciences have demonstrated the fundamental mechanisms that govern the operation of OCS.

These mechanisms elucidate OCS functionality and bolster the efficacy of carbon sink enhancement efforts, achieved through the use of models, as well as a range of monitoring and restoration technologies. Simultaneously, the social sciences establish a correlation between the scientific value of OCS and human society, thereby offering value assessment, incentive mechanisms, and governance frameworks to facilitate science-driven

TABLE 2 Clustering information of keywords networks.

Cluster ID	Size	Sihouette	Mean (Year)	Label (LLR)
0	42	0.732	2013	carbon sink (12.64, 0.001); carbon emission (8.39, 0.005); energy structure (8.39, 0.005); blue energy (4.18, 0.05); digital infrastructure (4.18, 0.05)
1	37	0.985	2010	sources of uncertainty (4.96, 0.05); levelized cost of energy (4.96, 0.05); carbon dioxide emissions (4.96, 0.05); immunology (4.96, 0.05); fuels (4.96, 0.05)
2	35	0.882	2017	adaptation (8.63, 0.005); carbon dioxide removal (8.63, 0.005); negative emissions (8.63, 0.005); greenhouse gases (4.3, 0.05); added value products (4.3, 0.05)
3	33	0.963	2016	deep biosphere (10.59, 0.005); reactivity (10.59, 0.005); marine sediments (10.59, 0.005); microorganisms (10.59, 0.005); organic carbon (10.59, 0.005)
4	33	0.985	2015	oil and gas (5.33, 0.05); anaerobic digestion (5.33, 0.05); carbon capture and storage (5.33, 0.05); phycocyanin (5.33, 0.05); biofuels (5.33, 0.05)
5	26	0.992	2014	microstructure (6.89, 0.01); net zero emissions (6.89, 0.01); early evolution (6.89, 0.01); genetic engineering (6.89, 0.01); valorization (6.89, 0.01)
6	22	1	2011	testbed mooring site (6.75, 0.01); nitrate (6.75, 0.01); wave (6.75, 0.01); Yangtze platform (6.75, 0.01); high resolution (6.75, 0.01)
7	21	0.859	2002	photosynthetic pathways (9.6, 0.005); aquatic (9.6, 0.005); grasslands (9.6, 0.005); succulents (9.6, 0.005); blue carbon (0.15, 1.0)
8	21	0.973	2017	blue carbon (8.36, 0.005); Paris Agreement (5.63, 0.05); urban sustainability (4.6, 0.05); pollution (4.6, 0.05); air quality (4.6, 0.05)

TABLE 3 Citation counts of keywords networks.

Citation counts	Node name	Cluster ID
26	climate change	2
19	blue carbon	8
13	carbon dioxide	1
8	carbon	0
8	organic carbon	3
8	coastal	2
8	carbon sink	0
8	carbon capture	4

management practices (Howard et al., 2017). Achieving sustainable utilization of OCS necessitates a multifaceted collaborative effort.

Bibliometric analysis tools allow for the systematic categorization of research content and the examination of developmental trajectories, collaborative networks, research intensity and the evolution of hotspots in OCS studies. They also facilitate close reading of key literature details. Through these methods, research contents can be systematically categorized into three overarching topics: the main classification and functions in adapting to climate change, the scientific status and diverse carbon sequestration technologies, and the governance of carbon sinks within socio-political contexts.

Topic I: The Main Classification and Functions in Adapting to Climate Change of OCS

Classifying OCS and elucidating its functions in adapting to climate change constitute the primary tasks to be addressed first in bibliometric analysis. The oceans play a pivotal role in the global carbon cycle by absorbing atmospheric CO₂ through both direct and indirect processes (Turrell et al., 2023). These processes can be

categorized into three distinct categories: physical carbon pump, biological pump, and carbonate pump, depending on the underlying driving factors. The oceans' capacity to directly dissolve and sequester CO₂ involves complex biological and physical processes. The dissolution of CO₂ by surface seawater is the initial step in this process, followed by its transportation and storage across the global ocean through various physical processes such as circulation, mixing, and sedimentation. This phenomenon, known as the physical carbon pump, plays a crucial role in regulating the ocean's carbon balance (Huiskamp et al., 2016). The indirect pathway functions through two distinct mechanisms. First, marine organisms fix inorganic carbon into organic carbon through photosynthesis. Then, residual biomass sinks, and microbial decomposition partially mineralizes the organic carbon back into inorganic carbon. This process is known as the biological pump. Conversely, marine organisms sequester inorganic carbon as carbonates through a process known as calcification, thereby constituting the carbonate pump (Neukermans et al., 2023; Siegel et al., 2023).

These different types of ocean carbon pumps are distributed across coastal areas, offshore continental shelves, open oceans, deep seas, and polar regions. The primary ecosystems contributing to coastal carbon sinks include mangroves, seagrasses, salt marshes, seaweeds, and coral reefs, among others. Wetlands have been identified as a significant potential carbon storage and sequestration site. Moreover, they deliver a variety of crucial ecosystem services (Arifanti et al., 2022; Temmink et al., 2022; Martin et al., 2023; De et al., 2024; Ureta et al., 2024; Xiang and Cao, 2024). Long-term carbon stocks in offshore or shelf sediments are comparable to those found in tropical forests, but the exact capacity of these sediments to store carbon depends on the type of sediment (Christianson et al., 2022). Deep-sea carbon sequestration, which involves forming stable CO₂ hydrates in the ocean depths that can withstand even the most intense earthquakes and other geological

Top 11 Keywords with the Strongest Citation Bursts

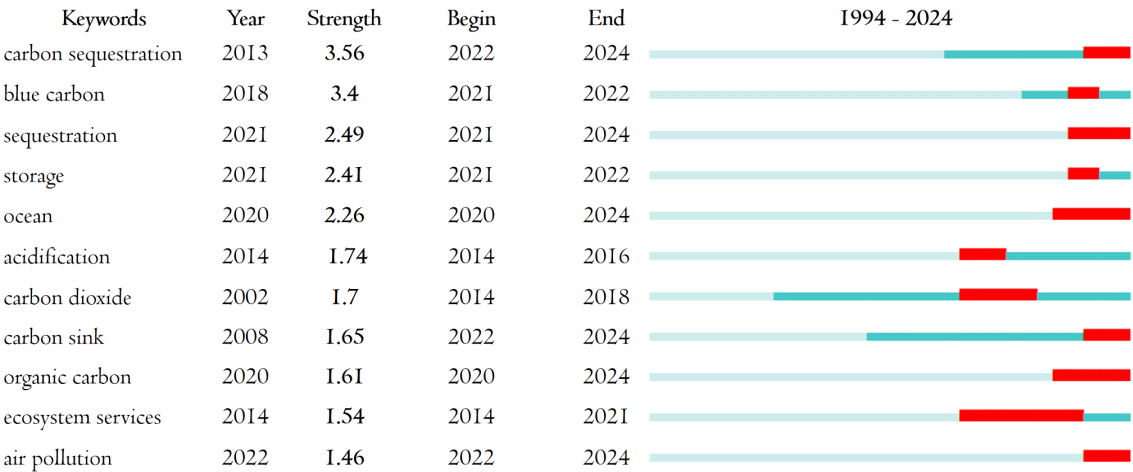


FIGURE 7
Top 11 keywords with the strongest citation bursts.

disturbances, represents the most promising method for future carbon sequestration (Zou et al., 2023). The polar regions, particularly Antarctica, hold immense potential as a carbon sink (Gogarty et al., 2020). Climate warming has caused the retreat of Antarctica's ice sheets and the disintegration of its ice shelves. This has, to some extent, enhanced the capture and storage of CO₂ in its bottom sediments and benthic ecosystems. Consequently, it has expanded the carbon sequestration potential of the global OCS and increased the scale of the carbon cycle.

Marine fisheries have the dual attributes of “carbon source” and “carbon sink” (Wang and Feng, 2023; Song et al., 2024), with mariculture serving as the primary carbon sink. Moderate aquaculture of seaweeds, shellfish, and other marine organisms can enhance the efficiency of carbon uptake and removal by these organisms, thereby accelerating the functioning of the biological pump (Zhang et al., 2021). Simultaneously, this process converts atmospheric and oceanic inorganic carbon into organic matter, thereby increasing the capacity for carbon storage (Jin et al., 2024). However, large-scale aquaculture may release excess CO₂ that amplifies its carbon source properties (Song et al., 2024). Overfarming depletes excess nutrients from local waters, affecting the ocean's nutrient chemistry (De et al., 2024).

Environmental governance issues related to oceans, climate, and biodiversity are becoming increasingly interconnected. There is a growing recognition that reducing ocean-based carbon emissions, mitigating the impacts of climate change, and achieving sustainable development are all interrelated and mutually reinforcing (Contreras and Thomas, 2019). With the ocean capturing, utilizing and sequestering CO₂, regulating the climate system, ocean-based ecosystem approaches can provide insight into the impacts of carbon fluxes and the sea-air carbon cycle on climate change (LaRowe et al., 2020). OCS has a strong capacity for adaptation (IPCC, 2007; Simane et al., 2012). OCS is also quite sensitive to climate change as many marine organisms are fragile and often influenced by climate changes and human activities (Macreadie et al., 2022; Gruber et al., 2023). Marine protected areas, as a fundamental and useful tool to assist in managing OCS as well as marine ecosystems, are an effective way of mitigating regional carbon stressors, ensuring sustainable use of natural resources (Cziesielski et al., 2021; De et al., 2024).

Topic II: The Scientific Status and Technological Evolution of OCS

OCS represents a multifaceted challenge within an interdisciplinary framework. The scientific advancements that are embodied by these phenomena are, in essence, a critical manifestation of technological development in the mitigation and adaptation to climate change. Consequently, delineating and synthesizing the scientific status represents a critical task for bibliometric analysis of scientific research related to OCS. The governance of OCS must be grounded in a robust scientific foundation (McCormack et al., 2016), and scientific research has the potential to profoundly enrich our understanding of OCS.

Nature-based OCS, such as seagrasses, mangroves, and salt marshes, have been shown to exhibit the characteristics of high-efficiency carbon sequestration, with their carbon sequestration rate

being approximately 2–4 times that of mature tropical terrestrial forests. Marine plankton, comprising entities such as diatoms, has been determined to account for approximately 20% of global net primary productivity (Reiter et al., 2021; Schweitzer et al., 2021; Gandhi et al., 2024). Additionally, the carbon storage capacity of surface sediment and the water column is estimated to be approximately 13 to 21 times greater than that of terrestrial soils (Turrell, 2019). Anoxic marine zones, while inhospitable to most marine life, offer ideal geological conditions for CO₂ sequestration (Wu et al., 2019; Puro.earth, 2025). These zones feature stable sedimentary layers and minimal biological disruption, conducive to long-term carbon storage. However, effectively monitoring and verifying the carbon sequestration capacity of these areas still require highly advanced and mature technologies. In recent years, Antarctica has emerged as a significant carbon sink, primarily due to the retreat of sea ice. This phenomenon promotes carbon accumulation through two distinct mechanisms. Firstly, the replacement of high albedo ice with seawater enhances the physical absorption of CO₂ by the ocean. Secondly, the loss of more permanent ice shelves and glacier retreat enables the colonization of entire benthic (seabed) assemblages, thereby enhancing the ecological diversity and the system's capacity to accumulate carbon (Gogarty et al., 2020).

Artificial enhancement of OCS is also of great significance for reducing carbon footprint and boosting carbon sequestration potential, with examples including seawater desalination, marine aquaculture technology, ocean alkalization, marine ecosystem restoration (e.g., coral reef restoration and seaweed restoration), and artificial upwelling (Pan et al., 2016; Shokri and Sanavi Fard, 2023; Castilla-Gavilán et al., 2024; De et al., 2024). Ocean iron fertilization (OIF) involves adding iron to high-nutrient, low-chlorophyll regions to stimulate phytoplankton growth and enhance oceanic carbon sequestration capacity. However, due to the limited bioavailability of iron, the effectiveness of OIF remains controversial (Boettcher et al., 2021; Jiang et al., 2024). These artificial carbon enhancement technologies inevitably pose unpredictable ecological risks. For example, mariculture can lead to marine oligotrophy; ocean alkalization can release heavy metals, thereby increasing the risk of environmental pollution; artificial upwelling can exacerbate ocean acidification; and OIF can cause imbalances in phytoplankton communities and have a knock-on effect throughout food chains (McCormack et al., 2016; Fuss et al., 2018; De et al., 2024). All of these factors disrupt the marine ecosystem. Furthermore, even if certain concepts are scientifically valid, practical economic factors must still be considered. For example, although microalgal biofuels have advantages, they are associated with high costs and uncertain market demand (Chen et al., 2020). Given the numerous unknown variables, the governance of artificial carbon enhancement must strengthen risk management and control efforts to balance ecological risks and economic feasibility.

Technological progress is one of the fundamental driving forces behind the advancement of scientific knowledge (Galvez and Gaillardet, 2012). Carbon capture, utilization and storage (CCUS) and CO₂ removal (CDR) are two technological pathways for

reducing CO₂ and addressing climate change issue, and they also represent important manifestations of the carbon sink function of the oceans. Among them, CDR emphasizes the elimination of extant CO₂ from the atmosphere, with the overarching objective of diminishing atmospheric stocks. CCUS and CDR are not absolutely distinct, as they overlap in the specific technical scope and provide synergy between emissions reductions and carbon removal, with both critical for reaching net-zero (Deich and Wilcox, 2025). Within the CCUS technology framework, the mainstream technologies for ocean carbon capture include pre-combustion capture, post-combustion capture, oxy-combustion capture, chemical loop combustion, and direct air capture. The key technologies for ocean carbon sequestration encompass seawater sequestration and marine geological sequestration, where marine geological storage involves injecting CO₂ into depleted oil and gas reservoirs, salt caverns, saline aquifers, and other similar marine environments (Shaw and Mukherjee, 2022; Ampomah et al., 2024). Within the CDR technology framework, the recognized technologies primarily include afforestation and reforestation, soil carbon sequestration, marine biomass and blue carbon, direct air capture with carbon storage, bioenergy with carbon capture and storage, enhanced weathering, and biochar (Sovacool et al., 2023; Tripodi et al., 2024).

The oceans are vast, but there are currently insufficient spatial and temporal observations of surface ocean CO₂ and airborne CO₂ fluxes, especially in winter and in high latitude areas, resulting in the fact that we know very little about long-term changes in the physical, biological, and chemical processes that underlie OCS (Duke et al., 2023). The Global Ocean Observing System has already provided an increasing amount of open type data about CO₂. Observation results of coastal zones and high seas will be included in integrated management platforms (e.g., Eulerian and Lagrangian platforms) in the future to predict trends in CO₂ and seawater temperatures to support relevant ocean decision-making (Grégoire et al., 2021). Many new data and analysis techniques are increasingly being used to quantify coastal risks and others, such as using satellite imagery and machine learning to improve the accuracy of habitat classification, using drones for monitoring after natural disasters, or intervening in ocean management processes in advance (Ruckelshaus et al., 2020). The integration of carbonate system sensors with built-in sensors and other sensors has been demonstrated to enhance observation efficiency and spatial coverage (Osborne et al., 2022; Lin et al., 2024). Airborne LiDAR bathymetry can meet the needs of large-scale integrated mapping of land and ocean, and will develop towards system miniaturization and unmanned platforms in the future (He et al., 2024). Models are a powerful tool for studying the carbon cycle and its response to climate change (Aumont et al., 2015). Drawing on relevant data and employing model simulations, analyzing the variability of carbon sinks at fine spatial and temporal scales can enable us to quantify the carbon sink capacity in different regions. Furthermore, it allows us to forecast how the carbon sink capacity of the OCS will change in the future under various climate scenarios (Lai et al., 2022; Gruber et al., 2023).

In addition, effective ways to reduce technological emissions of CO₂ include reducing the demand for fossil energy or using alternative clean energy sources (Almomani et al., 2023). These new energy sources have the potential to power navigation, communication equipment, and related systems and devices on floating structures, thereby reducing their carbon footprint (Pires Manso et al., 2023). Conversely, the Neutral Buoyant Sediment Trap has been demonstrated to be a more precise instrument for the study of carbon flux (particularly biological carbon flux) by autonomously adjusting buoyancy to drift at the target depth, thereby reducing water flow interference (Estapa et al., 2020). Ocean energy has the technical potential to reduce CO₂ and the commercial viability to support economic growth (Magagna and Uihlein, 2015). Integrating ocean energy into the marine industry is essential for reducing carbon emissions and adapting to global climate change (Pan et al., 2024).

Topic III: Governance Risks of Sustainable Scientific Research on OCS

With respect to governance risks, academic articles on scientific advancements in OCS rarely reflect public management in their titles or keywords. Nevertheless, they consistently address governance-related risks and ethical considerations within their analyses, underscoring the intrinsic inseparability between the natural and social sciences. This means that although OCS is primarily focused on scientific research, it will inevitably need to be integrated with public management at a certain stage of development in order to achieve climate justice. Discussions on the ethics, morality, and justice of OCS have been marginalized in practice (Gonzalez et al., 2021). In many countries, mangroves, seagrasses, estuaries and salt marshes have been disturbed by commercial shrimp farming and fish farming (Castilla-Gavilán et al., 2024). There is also some invisible gender discrimination in some shrimp farming systems (Nguyen et al., 2022).

Integrating scientific and technological progress into policy relies heavily on the mutual trust and cooperation of stakeholders (Bastardie et al., 2023). Comprehension of the perspectives held by stakeholders is of paramount importance, as it facilitates a more profound examination of the viewpoints held by all relevant parties and helps address existing power imbalances in research (Rivers et al., 2023). This understanding enables the prediction of reactions by social groups to new policies and marine conservation plans, thereby supporting stakeholder-oriented policy initiatives in the cultivation of shared knowledge (Nikas et al., 2021; Quevedo et al., 2024). The aforementioned factors contribute to a more effective and inclusive decision-making process. The collaboration among government, local communities, and market stakeholders, whether top-down or bottom-up, is instrumental in ensuring the legitimacy and sustainability of the OCS system (Benani et al., 2025). It is particularly noteworthy that OCS projects furnish local communities with diversified livelihood opportunities, and the engagement of multiple stakeholders also advances women's economic empowerment, which in turn contributes to the practical realization of gender equality (Rasowo et al., 2024). However, various stakeholders harbor distinct needs and

expectations regarding the oceans, often characterized by divergent and even conflicting priorities and values (Dale et al., 2019). The commodification of ecosystem services and the simplistic financial valuation of coastal environments are often at odds with the cultural traditions, beliefs, and spiritual values of local communities. Moreover, such approaches may inadvertently perpetuate colonial-era power dynamics and relationships (Bennett et al., 2021; Reiter et al., 2021). The international community has recognized the global nature of OCS through its inclusion in coordinated agreements on emissions reduction and climate change mitigation. Additionally, harmonized institutions, such as the International Carbon Action Partnership (ICAP) and the Global Carbon Council (GCC), have been established to manage carbon sinks. Their creation was initially driven by the urgent need for global cooperation in this critical domain (Chen et al., 2024). However, the significant variability in global sea-air CO₂ fluxes could result in inequitable distribution, with some countries being allocated more carbon sink capacity while others are designated as carbon sources (Rickels et al., 2024).

Carbon trading can potentially provide an additional economic resource for both developing countries and local communities (He et al., 2023). OCS, distinguished by its enhanced carbon sequestration efficiency, extended storage lifespans, and considerable financing prospects, is widely regarded as a suitable commodity for carbon trading (Wang et al., 2024b). The financial proceeds from ocean carbon trading have been demonstrated to provide crucial support for coastal protection and the restoration of damaged habitats and their resident organisms. This, in turn, enables these organisms to maximize their carbon sequestration potential (Ewane et al., 2025). Furthermore, a portion of the revenue from ocean carbon credit trading could be redistributed to communities, providing them with sustainable financial support for conserving resources and ensuring the continued provision of ecosystem benefits (Vanderklift et al., 2019). However, the practice of ocean carbon trading has the potential to engender social risks as well. Blue carbon projects, for instance, generally entail substantial initial costs, but suffer from ambiguous legal stipulations on ownership and an absence of a conducive regulatory framework. Consequently, the return on investment for blue carbon projects may be minimal or even negative, thereby introducing financial risks to investors (Friess et al., 2022). In the context of the international carbon trading market, the prices prevailing in these markets often fall far short of what is necessary to adequately compensate developing countries for the economic sacrifices they make by relinquishing development opportunities to protect marine ecosystems (Reiter et al., 2021; Friess et al., 2022). There are ongoing challenges in achieving a balance between the protection of fundamental national economic interests and environmental justice.

OCS's functioning needs to be regulated and guided by law in order to minimize ethical, moral, and social risks. Marine ecosystems are inherently transboundary and interconnected. In contrast, science, technology and law each function as independent and self-generating systems (Jensen et al., 2022). As a result, OCS is governed by a complex web of fragmented and overlapping rules, which may result in conflicting legal interpretations. If a state

conducts ocean alkalization or fertilization within its jurisdictional waters to enhance the ocean's capacity to absorb atmospheric CO₂, other states may argue that such activities pose a significant threat of transboundary harm to the marine environment (Lin et al., 2024). Moreover, current international law does not yet provide a clear balance between the right to use the oceans beyond national jurisdiction as OCS and the obligation to protect the marine environment (Boettcher et al., 2021). This indicates that the existing international legal framework governing the oceans has limited capacity to address climate change at its source directly (Beringen, 2024). When coastal countries develop ocean management policies, the traditional customary rights of coastal residents frequently coexist with formal legal rights, resulting in a highly complex rights landscape that exacerbates institutional management conflicts (Dencer-Brown et al., 2022).

5 Discussion

Current scientific research on OCS includes (1) various sources of carbon sinks; (2) functions in mitigating and adapting to climate change; (3) the development of ocean observation, assessment, and prediction technologies; (4) the uncertainties about contribution of OCS, and (5) the governance challenges on OCS. Although scientific consensus on many of the technical issues related to OCS has not yet been fully achieved (Nellemann et al., 2009), a fundamental aspect of scientific progress lies in exploring the functions of OCS. This includes understanding the factors that influence these functions, as well as developing new approaches to enhance them (Li et al., 2024). OCS research is fraught with numerous uncertainties beyond the potential biases in modeling and data parameters (DeVries et al., 2023). This is particularly evident given the paradoxical situation where scientific understanding of the ocean's role in buffering climate change remains limited, public awareness is insufficient, and national policies often lack meaningful action. In this context, the intrinsic value of nature and the need for precautionary management are frequently overlooked (Hessen and Vandvik, 2022).

Assessments of OCS need to rely on natural ecosystems and nature-based solutions (NbS), which are currently important programs supporting scientific advances in this field (Zhang et al., 2024a). NbS have been incorporated into the mitigation and adaptation plans of nearly two-thirds of the parties to the *Paris Agreement*, and are often hailed as the "key" to achieving net-zero carbon emissions (Hoffman, 2023). Compared to technological solutions such as geoengineering, utilizing naturally occurring carbon fixation, storage, and sequestration to mitigate and adapt to climate change may be a lower-risk and lower-cost strategy (Martin et al., 2021). OCS is constrained by the uncertainties arising from multidisciplinary interactions across scientific, social, economic, and ecological dimensions. Moreover, the concept of precaution, closely related to these uncertainties, has not yet been thoroughly explored in this context. Precaution has the ability to anticipate, monitor, and mitigate potential threats (Dale et al., 2019; Ogawa and Reyes, 2021). Implementing precautionary management of

the risks associated with the advancement of OCS can enhance the adaptive capacity of symbiotic marine organisms to climate change (Chan et al., 2021). The multifunctionality of the ocean underscores its value beyond carbon sequestration. OCS contributes to ecosystem resilience, supports biodiversity, enhances environmental functions, and generates socioeconomic benefits (Rosentreter et al., 2021; Martin et al., 2023; Fermepin et al., 2024). These co-benefits are integral to the value proposition of OCS (Barua et al., 2024). Yet current governance structures often place additional burdens—environmental, economic, and ethical—on vulnerable groups, raising concerns of scientific and climate justice (Nellemann et al., 2009). While scientific advancements are critical for informed policy, they risk becoming fragmented and disconnected from social contexts when they become overly specialized (Smetacek, 2018). Therefore, future progress in OCS research must adopt a systems-based, precautionary approach by integrating top-down governance with bottom-up ecological restoration.

Restoring marine ecosystems strengthens carbon sinks while also advancing economic development, enabling synergies between environmental and social goals (Benayas et al., 2009). Such integrative approaches not only enhance the effectiveness of carbon sink functions but also create pathways for inclusive and adaptive ocean-land governance frameworks. In this way, scientific innovation in OCS can contribute meaningfully to broader ocean-land sustainability transitions.

6 Conclusion and suggestions

The ocean is the largest ecosystem on Earth and a stable, long-term net carbon sink (Archer et al., 2009; Britton et al., 2021; Shutler et al., 2024). Significant progress has been achieved in the scientific research related to OCS. However, its interdisciplinary nature has introduced considerable uncertainties at the governance level. We have identified the key issues in the related research by conducting a comprehensive review of the literature on the scientific advancements in OCS. As a scientific proposition, OCS is also rooted in the social sciences (Sovacool et al., 2023). The interdisciplinary nature of OCS and the continuous evolution of science and technology suggest a need for specific recommendations to guide future research in this field.

Firstly, improving the technological application in the scientific research on OCS. Despite the scientific uncertainty, technology has the potential to reduce carbon intensity (Waheed, 2022). Therefore, in terms of observation, high-precision, high spatiotemporal resolution, and long-time-series carbon flux monitoring technologies support continuous ocean observation. We can achieve efficient, convenient and traceable data collection by integrating technologies such as satellites, sensors, drones and radars for carbon monitoring across a range of spatial and temporal scales (Brown et al., 2023). Regarding data integration, we could develop a big data scientific platform that incorporates the collection, storage, calculation, and analysis of domestic and international carbon sink data. This platform should have standardized interfaces and tiered access permissions for governments, research institutions, and enterprises to facilitate the flow of carbon sink data among different governance bodies (Liu et al.,

2022b). Regarding modeling optimization, we should regularly select *in-situ* observation data from various marine areas to calibrate the parameters of OCS models and promptly correct the spatial interpolation biases of the models. This balances the accuracy and scope of OCS data.

Secondly, encouraging multi-stakeholders to participate in the “sea-gas” cycle. To begin with, environmental education is a key component in promoting extensive participation by stakeholders (Hilser et al., 2024b). The government should enhance the scientific understanding of the ecological value of marine systems among private stakeholders and deepen their comprehension of marine ecological changes through public education and awareness campaigns. Furthermore, successful coastal management also necessitates the “valorization” and “mainstreaming” of decarbonization efforts (Atchison et al., 2024; Shutler et al., 2024). Managers must consider the diverse needs of various stakeholders, develop more progressive ethical guidelines that strike a balance among the basic survival needs of coastal communities, the demands of commercial interests, and the imperative for a clean environment. Ultimately, the establishment of a conduit between scientific data and the requirements of stakeholders enables enhanced decision-making processes in the context of carbon management (Brown et al., 2023). To this end, countries can collect insights on OCS and its governance from stakeholders, including research institutions, enterprises, and local community residents, to inform domestic scientific decision-making. When engaging in joint OCS conservation efforts, the international community should prioritize the unique ecological and political interests of underrepresented regions, such as small island developing states, to facilitate sustained marine dialogue (Dobush et al., 2022; Hilser et al., 2024a). Scientific cooperation among regional countries on OCS can also alleviate geopolitical tensions (Ampomah et al., 2024; Patra et al., 2024).

Thirdly, building policy-based financial system to support scientific advances on OCS. Scientific research on OCS entails significant technological costs, suggesting that projects are unlikely to succeed without the provision of commercial services beyond carbon sequestration (Thomas, 2014; Cziesielski et al., 2021). Moderately integrating OCS into the carbon trading market could be achieved by launching blue carbon derivatives, such as futures and options, based on the existing spot trading system. This would activate capital liquidity and facilitate the reduction of carbon emissions (Gao et al., 2023). The government can comprehensively control carbon emissions through policy. In addition to formulating legal frameworks for OCS protection, the government can provide policy subsidies for blue carbon projects through loan interest subsidies, tax reductions and exemptions, and preferential interest rates (Dobush et al., 2022). These measures can significantly enhance the efficiency of OCS scientific research.

OCS is not only vital for climate regulation but also for achieving nature-based, cross-system solutions to global sustainability challenges. Based on bibliometric analysis, this study synthesizes and summarizes the current scientific status and governance issues of OCS, as well as offering insights into its future development. However, it is important to acknowledge the inherent

limitations of this approach. As a multidisciplinary research endeavor encompassing both natural and social sciences, scientific innovation is characterized by its rapid and ongoing nature. Consequently, there is a notable lag in the pace of academic research in keeping pace with these advancements. As a result, the findings may not yet fully reflect the most recent scientific advancements. Moving forward, advancing OCS research requires technological innovation, inclusive stakeholder governance, and robust policy-based financial system. Only through integrated and precautionary approaches can the ocean's full carbon sequestration potential be realized—complementing land-based efforts to build a resilient and low-carbon future.

Author contributions

HW: Writing – original draft, Software, Visualization, Investigation, Methodology, Formal analysis. YD: Writing – original draft, Conceptualization, Validation, Supervision, Project administration. UPKE: Writing – review & editing. BB: Writing – review & editing. BS: Writing – review & editing. HZ: Writing – review & editing, Supervision. HS: Writing – review & editing, Supervision, Conceptualization, Validation, Resources, Project administration, Funding acquisition.

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