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Mapping the research framework and key trends of coral reefs in the South China Sea

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The South China Sea, a key biodiversity hotspot in the Central Indo-Pacific, hosts a rich array of coral reef species and marine life but faces growing threats from climate change and human activities. This study systematically analyzes coral reef research in the region using a bibliometric analysis of records from the Web of Science Core Collection. The analysis highlights the diverse roles of contributing countries and their collaborations, with China emerging as a significant contributor to the regional scientific output. Our findings categorize the research into five principal themes through text mining and bibliographic coupling: (1) fundamental physical-biological interactions within reef systems, (2) biodiversity and symbiotic relationships in response to environmental stress, (3) climatic influences and the adaptive responses of reef systems, (4) conservation strategies and management practices for reef resilience, and (5) remote sensing and algorithmic approaches for reef mapping and monitoring. The discussion addresses regional challenges, outlines the identified research framework, and details key trends in South China Sea coral reef research, thereby providing essential information to guide future development and conservation efforts.

KEYWORDS

coral reefs, South China Sea, bibliometric analysis, climate change, research development

1 Introduction

The South China Sea, encompassing over 3 million km² within the Central Indo-Pacific marine realm, is a critical hotspot for global coral reef biodiversity (Morton and Blackmore, 2001; Spalding et al., 2007). Southeast Asia, widely recognized as the global epicenter of coral reef diversity, contains approximately 34% of the world's coral reefs despite occupying only 2.5% of the Earth's total sea surface (Arai, 2015). Within this region, the South China Sea supports more than half of Southeast Asia's hard coral species diversity, hosting 571 known reef coral species—a richness comparable to that of the adjacent Coral Triangle, despite comprising less than 17% of its reef area (Sanciangco et al., 2013; Huang et al.,

2015). The region is also home to 3,365 marine fish species, accounting for 12% of the global fish catch and supporting the livelihoods of at least 3.7 million people through fisheries that rely on 55% of the world's fishing fleet (Raymond and Welch, 2022). These coral reefs provide essential ecosystem services, including biodiversity maintenance, tourism, and coastal protection, providing habitat or food for an estimated 25% of all marine species (Hughes et al., 2017). Coral reefs also function as natural coastal defenses, reducing erosion and buffering against storm impacts. Furthermore, they are vital breeding and nursery grounds for both open-ocean and bottom-dwelling fish species, which in turn support regional capture fisheries (Oakley and Pilcher, 1996; Arai, 2015; Yuan et al., 2024).

Despite their ecological and socioeconomic significance, the coral reefs of the South China Sea face mounting pressures from both environmental degradation and geopolitical tensions (Xiao et al., 2022). For decades, territorial disputes involving China, Vietnam, the Philippines, Malaysia, Indonesia, and Brunei have persisted, with overlapping claims to territorial and maritime jurisdiction remaining unresolved (Welch, 2017). These conflicts, compounded by strategic interests from non-claimant states such as the United States, which champions freedom of navigation and the rule of law, have impeded cohesive conservation efforts (Raymond and Welch, 2022). Consequently, the South China Sea has received less conservation focus than the Coral Triangle, despite its comparable biodiversity and critical role in supporting human populations (Sanciangco et al., 2013).

Given these challenges, effective management of the South China Sea's coral reefs requires a comprehensive understanding of existing research efforts. This study employs a bibliometric approach to systematically review research on coral reefs in the South China Sea, utilizing records from the Web of Science Core Collection. By analyzing publication trends, thematic priorities, and collaborative networks, we aim to map the evolution of the field and highlight key research areas. This synthesis provides a scientific basis for informing future research directions and management strategies to protect these vital ecosystems amid ongoing geopolitical and environmental pressures.

2 Methodology

2.1 Data

In order to extract as many relevant studies as possible from the target literature, using a well-structured research protocol has been widely highlighted in the literature as one of the most important prerequisites in conducting systematic reviews. On this basis, a structured search string was formulated using different combinations of the keywords "coral reefs" and "South China Sea" as the two main concepts that shape the present review. Considering the South China Sea is a politically sensitive and geographically complex area, with different countries and regions adopting distinct names and territorial claims, the various names and geographic terms used to refer to the South China Sea in different countries and regions were designed. Consequently, the following search string was constructed to collect articles from the Web of Science database: ("coral reef*" OR "reef-building coral*" OR "coral ecosystem*" OR "coral reef* ecosystem*" OR "coral community*") AND ("South China Sea" OR "SCS" OR "Xisha*" OR "Nansha*" OR "Zhongsha*" OR "Paracel Islands" OR "Spratly Islands" OR "Scarborough Shoal" OR "Huangyan*" OR "Weizhou Island" OR "Dongsha*" OR "meiji*" OR "Yongxing*" OR "Macclesfield Bank"). The inclusion of terms such as "Xisha," "Nansha," and "Zhongsha" reflects the Chinese terminology, while "Paracel Islands," "Spratly Islands," and "Scarborough Shoal" correspond to internationally recognized names or terms used in neighboring countries. Table 1 summarizes the steps taken in this research to construct the final sample. The exclusive use of the Web of Science database for this study was primarily driven by its reputation as a consistent and reliable dataset for bibliometric mapping. This choice aligns with established practices in various research fields, including studies on biomass energy, climate change vulnerability, and cultural heritage (Wang et al., 2014; Mao et al., 2018; Vlase and Lähdesmäki, 2023).

2.2 Analysis approach

Bibliometric analysis is a statistical method used to evaluate extensive scientific output and has become widely adopted for mapping research fields (Wang et al., 2014; Syamimi et al., 2022; Zeng et al., 2024). By establishing links among articles, journals, authors, keywords, citations, and co-citation networks, it helps researchers identify key themes, emerging trends, and potential future developments. In this study, we employed VOSviewer (version 1.6.19, developed by Van Eck & Waltman) to perform our bibliometric analysis (van Eck and Waltman, 2010). We then mapped the scientific output on coral reefs in the South China Sea, focusing on key indicators such as: (i) geographical distribution of publications, (ii) author productivity and influence, (iii) core journals, (iv) influential articles, and (v) keyword analysis to

TABLE 1 Steps of the data collection process.

Seach query	TS = (("coral reef*" OR "reef-building coral*" OR "coral ecosystem*" OR "coral reef* ecosystem*" OR "coral community*") AND ("South China Sea" OR "SCS" OR "Xisha*" OR "Nansha*" OR "Zhongsha*" OR "Paracel Islands" OR "Spratly Islands" OR "Scarborough Shoal" OR "Huangyan*" OR "Weizhou Island" OR "Dongsha*" OR "meiji*" OR "Yongxing*" OR "Macclesfield Bank"))
Field mined	Article titles, abstracts, author keywords, and keywords plus
Database	Web of Science
Document types	Article, Proceeding Papper, and Review Article
Search date	March 15, 2025
Sample	769

uncover research trends and focal points. Additionally, we conducted a text mining analysis using a term co-occurrence algorithm on the titles and abstracts of 769 articles, utilizing the text mining module of VOSviewer (van Eck and Waltman, 2011), to further refine our sample.

The constructure of the map involves three key steps. Firstly, a similarity matrix is computed from the co-occurrence matrix. This process involves assessing the similarity between each pair of items by evaluating the frequency of their co-occurrences relative to their individual or joint occurrences with other items. Second, the VOS mapping technique positions items in a low-dimensional space by minimizing a weighted sum of squared Euclidean distances between all pairs, subject to the constraint that the average distance equals one to prevent trivial layouts. Finally, to overcome local optima, the resulting configuration is translated, rotated, and reflected, which preserves relative distances while ensuring a globally optimized solution (van Eck and Waltman, 2010). All the analysis is accomplished in the VOSviewer software.

3 Results

3.1 Results of literature quantity analysis

As can be seen from Figure 1, three distinct stages can be identified. Research on coral reefs in the South China Sea started relatively late, with the first related publications appearing in 1987. Before 2013, the number of publications fluctuated at a low level, with an average annual count of fewer than 20. From 2013 to 2019, the annual publication count increased steadily, ranging between 20 and 50. Since 2019, there has been a marked year-by-year increase in publications, reaching 101 papers by 2024. The count for 2025 only comprises publications up to March 15, which explains the lower figure.

3.2 Performance of countries, institutions, and authors

3.2.1 Cooperation network of countries

The spatial and geographic distribution of articles offers insight into the leading countries contributing to coral reef research in the South China Sea since 1999. A total of 45 regions have published articles in this field, with 42 of them forming part of a co-authorship network. Figure 2 illustrates the co-authorship network among these countries, where the size of each node represents the number of articles published by that region, and the thickness of the links reflects the strength of co-authorship ties between pairs of regions. Table 2 lists the top 10 regions ranked by the number of published articles, collaborating regions (number of links), total co-authored articles (total link strength), and the number of citations received.

As detailed in Table 2, *China* leads across all four metrics, with 550 published articles, 33 collaboration links, 167 co-authorships, and 9,682 citations. While the second and third positions vary by metric, *Taiwan, China* ranks fourth with 60 articles, 23 collaborating countries, 77 co-authorships, and 1,445 citations. *Malaysia* follows in fifth place with 58 articles, 19 collaborating countries, 64 co-authorships, and 784 citations. *Australia, the USA, Germany, Singapore*, and the *Netherlands* are consistently among the top 10 contributors across all four metrics, though their specific rankings vary. As shown by the strength of the links in Figure 2, *China*'s strongest collaborative ties are with the *USA* (38 co-authorships) and *Australia* (34 co-authorships), representing the most significant partnerships within the network.

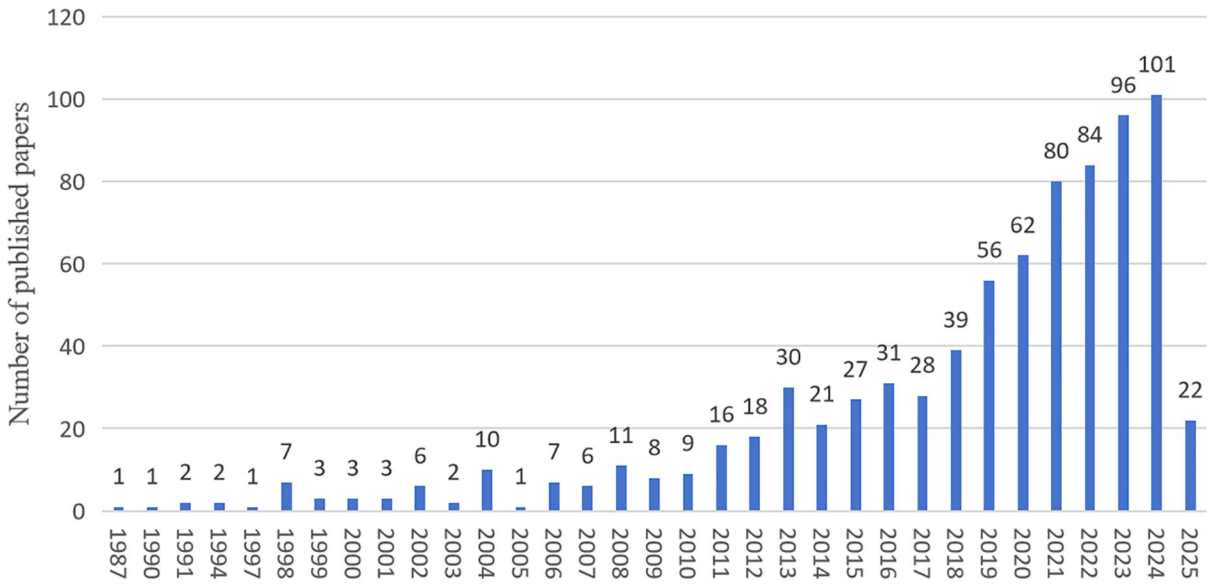

FIGURE 1
Distribution of coral reef publications in the South China Sea.

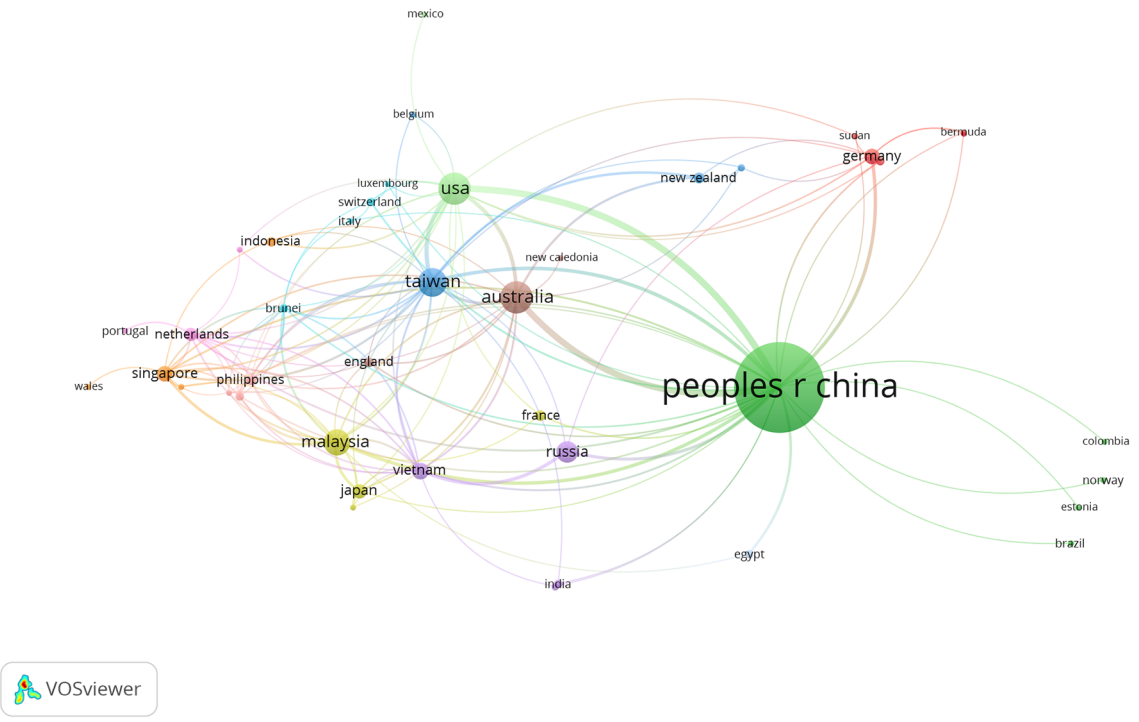

FIGURE 2
The countries' co-authorship network of coral reef research in the South China Sea.

3.2.2 Cooperation network of authors

Authors play a crucial role in evaluating the development of an academic field. A total of 2,661 authors have contributed to coral reef research in the South China Sea, with 112 authors having published at least five articles. Tables 3 and 4 list the most productive authors (based on the number of published articles) and the most influential authors (based on citation counts), respectively, along with their number of co-authors and co-authorships. According to these rankings, Yu Kefu is the most productive and influential author among the 2,661 contributors. Wang Yinghui ranks second in productivity and third in influence, while Huang Xueyong ranks third in productivity and second in influence.

3.2.3 Cooperation network of organizations

Understanding the leading organizations in a specific research area can be achieved by analyzing inter-organizational collaborations. To identify the key research institutions, we listed the top 10 organizations with the highest number of publications (Table 5) and created a co-authorship network map (Figure 3) using

TABLE 2 Top 10 regions in terms of the number of published articles, number of co-author region, total number of co-authorship, and the number of cites to their articles.

Rank	Published articles	Number of co-author countries	Total number of co-authorship	Citations
1	China (550)	China (33)	China (167)	China (9682)
2	Australia (71)	USA (25)	USA (97)	Australia (3405)
3	USA (70)	Netherlands (24)	Australia (86)	USA (2737)
4	Taiwan, China (60)	Taiwan, China (23)	Taiwan, China (77)	Taiwan, China (1445)
5	Malaysia (58)	Germany, Malaysia (19)	Malaysia (64)	Malaysia (784)
6	Russia (31)	Australia (17)	Netherlands (52)	Netherlands (749)
7	Vietnam (22)	Singapore, Vietnam (15)	Germany (40)	Germany (601)
8	Germany (21)	Philippines (14)	Singapore, Vietnam (38)	Russia (554)
9	Singapore (19)	England, Indonesia, Thailand (11)	Philippines (28)	Singapore (508)
10	Japan, Netherlands (18)	Brunei (10)	Russia (26)	Philippines (481)

TABLE 3 The most productive authors in the coral reef research in the South China Sea.

Author	Articles	Citations	Co-authors	Total co-authorship
Yu, Kefu	124	2489	51	420
Wang, Yinghui	39	1057	36	179
Huang, Xueyong	37	813	29	179
Huang, Hui	34	662	23	88
Chen, Biao	21	351	18	111
Shi, Qi	21	492	19	82
Bachok, Zainudin	19	131	4	25
Qin, Zhenjun	19	416	14	98
Zhao, Jianxin	18	449	20	57
Zhang, Ruijie	17	555	15	72

VOSviewer. Among the top 10 organizations, eight are from China, while the remaining two are from Australia and Malaysia. The Chinese Academy of Sciences leads with 250 publications, followed by Guangxi University with 113 publications. The other organizations have published fewer than 100 papers. In terms of Citations Per Paper (CPP), University of Queensland, ranked eighth in total publications, holds the highest CPP at 51.2. Xiamen University ranks second with a CPP of 22.5, followed by Chinese Academy of Sciences with 21 CPP.

Figure 3 shows the co-authorship network of research organizations, where each node represents an organization, with the node size indicating the number of publications. The thickness of the connecting lines reflects the strength of collaboration between two organizations. The Chinese Academy of Sciences appears as the largest node, followed by the University of Chinese Academy of Sciences and the Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou). The Chinese Academy of Sciences also has the strongest collaborative ties with other institutions, with its closest connection to the University of Chinese Academy of Sciences, followed by the Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou) and Guangxi University.

3.3 Performance of journals, citations, and keywords

3.3.1 Citation analysis on relevant journals

The 769 articles on coral reef research in the South China Sea within our dataset have been published in 275 journals. Among these, 42 journals have published at least five articles. Figures 4 and 5 present the top journals based on the number of published articles and citations, respectively. As shown in the figures, *Science of the Total Environment* leads in both the number of published articles and total citations. *Frontiers in Marine Science* ranks second in the number of published articles, while *Marine Pollution Bulletin* is the second most influential journal in terms of citations. Notably, there is a considerable gap between the second and third-ranked journals in both productivity and influence. Specifically, *Science of the Total Environment* and *Frontiers in Marine Science* have published 34 and

TABLE 4 The most influential authors in the coral reef research in the South China Sea.

Author	Citations	Articles	Co-authors	Total co-authorship
Yu, Kefu	2489	124	51	420
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Qin, Zhenjun	416	19	14	98
Chen, Biao	351	21	18	111
Bachok, Zainudin	131	19	4	25

TABLE 5 Organizations with the most publications in the coral reef research in the South China Sea.

Rank	Organization	Country	Publications	Proportion	Citations	Citations per paper
1	Chinese Academy of Sciences	China	250	38.6%	5238	21.0
2	Guangxi University	China	113	17.4%	1692	15.0
3	University of Chinese Academy of Sciences	China	89	13.7%	1327	14.9
4	Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou)	China	81	12.5%	566	7.0
5	Ministry of Natural Resources	China	42	6.5%	790	18.8
6	Universiti Malaysia Terengganu	Malaysia	34	5.2%	349	10.3
7	Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai)	China	33	5.1%	435	13.2
8	University of Queensland	Australia	32	4.9%	1638	51.2
9	Xiamen University	China	30	4.6%	675	22.5
10	Chinese Academy of Fishery Sciences	China	29	4.5%	146	5.0

33 articles, respectively, while *Marine Pollution Bulletin*, the third-ranked journal in terms of productivity, has published 24 articles. Similarly, in terms of citations, *Science of the Total Environment* and *Marine Pollution Bulletin* have received 670 and 657 citations, respectively, which are significantly higher than the 479 citations received by *Journal of Geophysical Research-Oceans*. This highlights *Science of the Total Environment* as the leading journal in coral reef research in the South China Sea.

3.3.2 The analysis on articles

This section presents two primary analyses, focusing on the citations received by the articles and their bibliographic coupling.

3.3.2.1 Influential articles

One way to assess the influence of an article in a specific research field is by examining the number of times it has been cited. Table 6 lists the top 10 most cited articles on coral reef

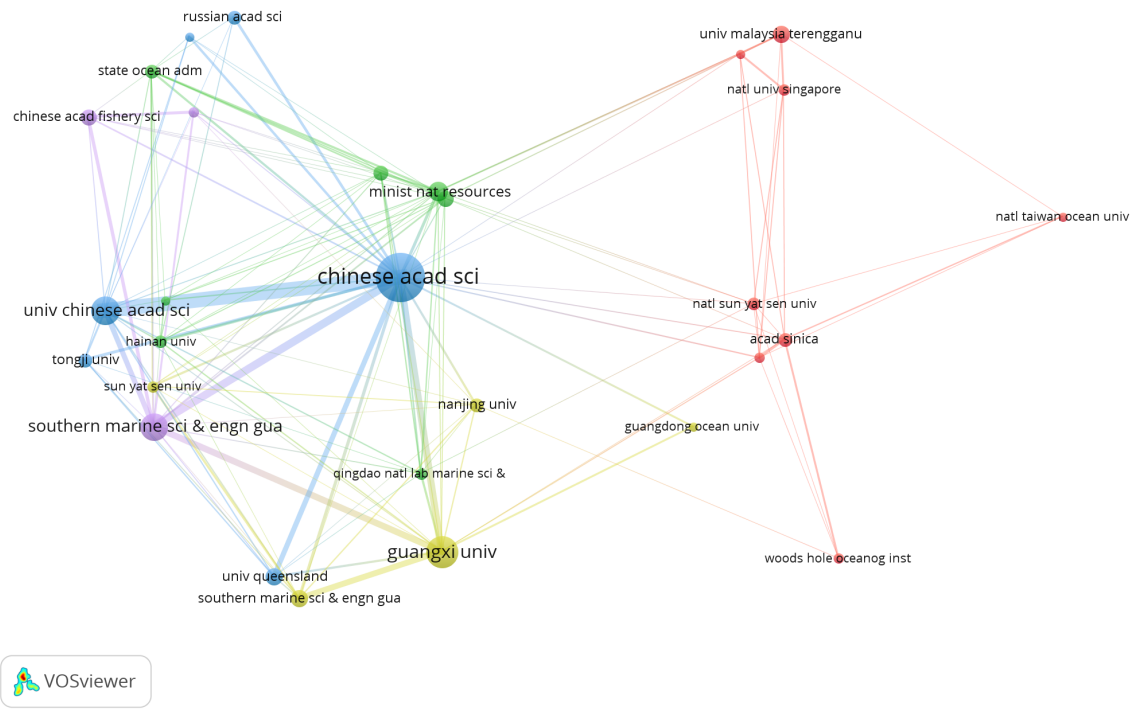

FIGURE 3
Mapping knowledge domain of coauthoring organizations in the coral reef research in the South China Sea.

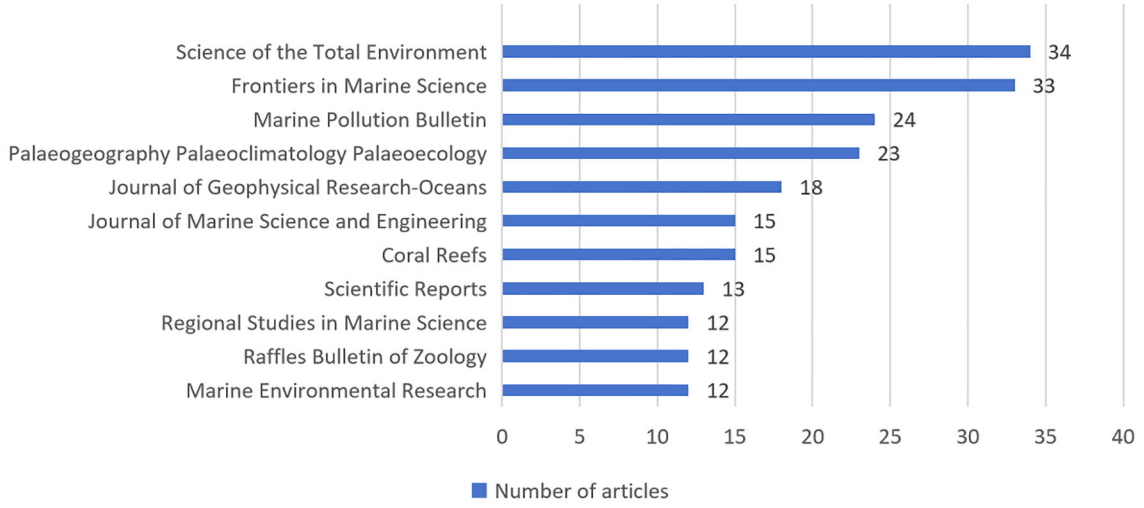

FIGURE 4
Top productive journals in terms of published articles.

research in the South China Sea. As shown in the table, the most influential article, with 630 citations, is a study by (Murray et al., 2019) that highlights the global loss, degradation, and fragmentation of coastal ecosystems, including coral reefs, tidal flats, and mangroves. Similarly, a global review of nutrients, metals, persistent organic pollutants, and major environmental changes driven by climate change and their effects on coastal ecosystems ranks eighth with 227 citations (Lu et al., 2018).

At the regional scale, several influential articles focus on the South China Sea and surrounding areas. Montaggioni (2005), explores the postglacial development patterns of Indo-Pacific coral reefs, ranking second with 366 citations. Liu (2013) examines the biodiversity of tropical coral reefs, securing the third spot with 322 citations. The South China Sea's biodiversity hotspots and associated challenges are discussed by (Morton and Blackmore, 2001), ranking fifth with 279 citations. Yu (2012) analyzes the ecological sensitivity and paleoenvironmental records of coral reefs in the South China Sea, ranking ninth with 206 citations.

Other influential studies focus on specific aspects of islands in the South China Sea. Wang et al. (2011) investigate the geotechnical properties of calcareous sands from Yongshu Reef, placing fourth in influence. Ding et al. (2019) discuss microplastic contamination in the coral reef ecosystems of the Xisha Islands, ranking tenth.

Moreover, novel methods for monitoring coral reef ecosystems are also featured among the most influential articles. Ma et al.

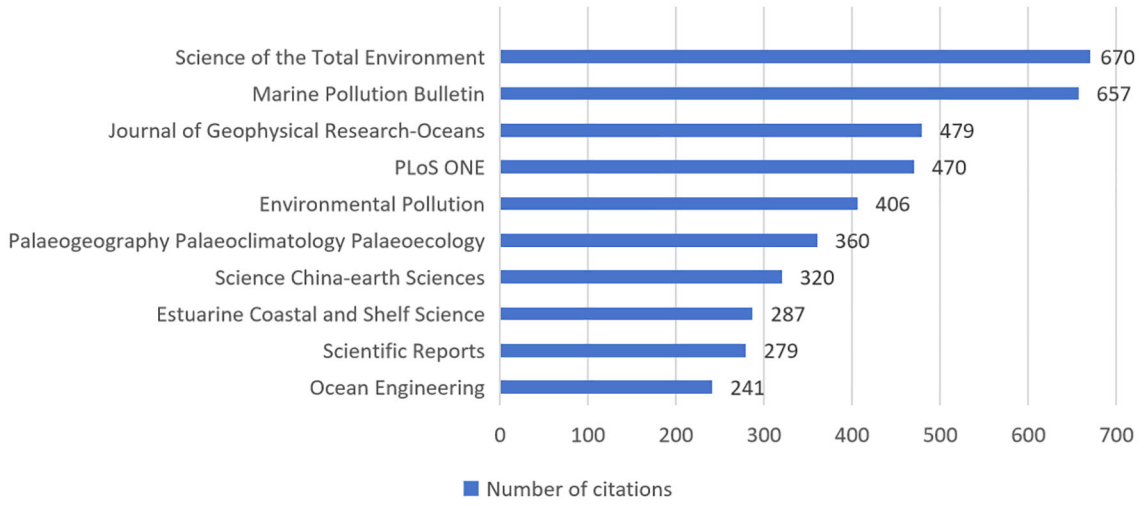

FIGURE 5
Top influential journals in terms of the number of citations to their articles.

TABLE 6 Top 10 highly cited articles in the coral reef research in the South China Sea.

Rank	Author	Title	Journal	Citations
1	Murray et al. (2019)	The global distribution and trajectory of tidal flats	Nature	630
2	Montaggioni (2005)	History of Indo-Pacific coral reef systems since the last glaciation: Development patterns and controlling factors	Earth-Science Reviews	336
3	Liu (2013)	Status of Marine Biodiversity of the China Seas	PLoS ONE	322
4	Wang et al. (2011)	Engineering characteristics of the calcareous sand in Nansha Islands, South China Sea	Engineering Geology	302
5	Morton and Blackmore (2001)	South China sea	Marine Pollution Bulletin	279
6	Li et al. (2021)	Deep-learning-based information mining from ocean remote-sensing imagery	National Science Review	238
7	Ma et al. (2020)	Satellite-derived bathymetry using the icesat-2 lidar and Sentinel-2 imagery datasets	Remote Sensing of Environment	233
8	Lu et al. (2018)	Major threats of pollution and climate change to global coastal ecosystems and enhanced management for sustainability	Environmental Pollution	227
9	Yu (2012)	Coral reefs in the South China Sea: Their response to and records on past environmental changes	Science China Earth Sciences	206
10	Ding et al. (2019)	Microplastics in the Coral Reef Systems from Xisha Islands of South China Sea	Environmental Science & Technology	187

(2020) introduces an approach integrating multi-satellite image analysis for empirical bathymetric mapping in shallow waters, validated in the Yongle Atoll, which ranks seventh. Li et al. (2021) propose using deep learning algorithms to extract coral reef information from underwater imagery, ranking sixth.

3.3.2.2 Bibliographic coupling of articles

In order to put the articles in relevant categories and show the main themes of the coral reef research, bibliometric coupling of the articles was conducted based on the references that they share. Out of the 769 research and review articles in our dataset, only 742 documents had at least one common reference with other documents. Therefore, these 742 articles were considered for the bibliographic coupling in this section. Figure 6 visualizes the articles grouped in three specific clusters, which was based on the Fractionalization method, with Attraction and Repulsion values set to 2 and -1, respectively. The Fractionalization method, by encompassing various similarity measures within a single parameterized formula, offers a unified framework that facilitates the comparison and interpretation of clustering outcomes (Van Eck and Waltman, 2009). These categories reflect strong internal connections between papers that share significant co-citations and thematic overlaps, identified through bibliographic coupling analysis. Each cluster is addressed by a different color and is named based on the main sense of the articles located in it. The size of the bubble points to the number of citations of the corresponding article and the link between each pair of articles shows their co-occurrence. The top 10 highly cited articles of each category are listed in Table 7.

The focus of the majority of the papers in research category A (red color in Figure 6) is on the multi-stressor impacts on coral reef ecosystems in the South China Sea. Coral cover in South China Sea has declined from an average of>60% to around 20% from 1990s to 2012 (Hughes et al., 2013). The increasing frequency and duration of marine heatwaves are closely linked to coral bleaching events, acting as a major stressor (Yao and Wang, 2021). Yu et al. (2012) further links historical bleaching episodes to El Niño-induced SST spikes, noting that recovery from mid-Holocene thermal stress required 10–30 years. Ocean acidification caused by rising atmospheric CO_2 levels (Dai et al., 2009) and microplastic contamination (Ding et al., 2019) place additional pressure on reef ecosystems. Moreover, nutrient enrichment from agricultural runoff (Archana et al., 2018), typhoon-induced runoff (Herbeck et al., 2011), and terrestrial pollutants delivered to reefs through river plumes (Lu et al., 2018) have been shown to alter reef biogeochemistry, further hindering coral recovery.

Coral reef archives of environmental change represent a key focus of research category B, highlighted in green in Figure 6. These studies use coral skeletal geochemistry and stratigraphic records to reconstruct past environmental variations over multiple timescales, ranging from centennial-scale winter cooling events (Yu et al., 2004b) to 160-year cycles of extreme weather patterns (Yu et al., 2004a). Additionally, coral skeletal trace metal records, such as rare earth elements (REEs), Ba/Ca, and Mn/Ca ratios, help assess anthropogenic impacts on a decadal scale (Nguyen et al., 2013; Saha et al., 2016). Historical sea-level reconstructions have also been employed to trace reef initiation during the Early Miocene (Fan et al., 2020) and to evaluate its impact on carbonate platform evolution (Shao et al., 2017), while also providing insights into long-term shifts in reef communities (Montaggioni, 2005; Wilson, 2008).

Research category C (shown in blue in Figure 6) primarily comprises studies focused on multi-level biodiversity dynamics within coral reef ecosystems. Numerous authors have documented the high diversity of marine species in the South China Sea (McManus, 1994; Morton and Blackmore, 2001; Liu,

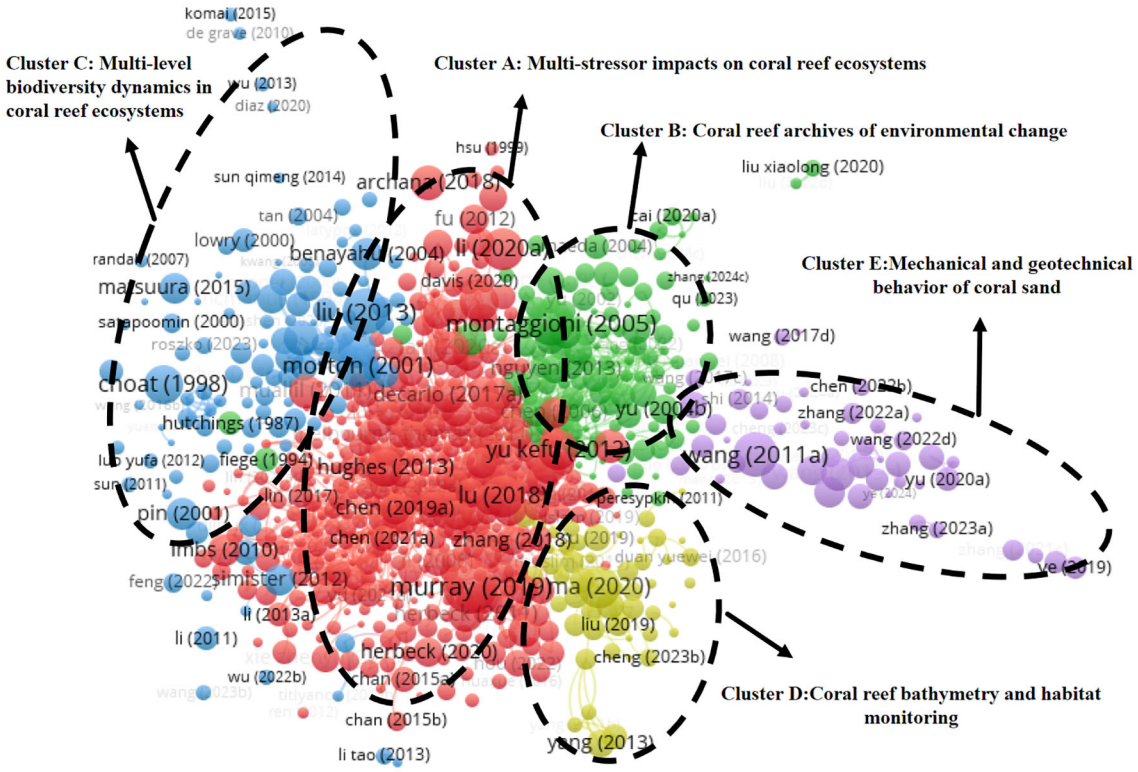

FIGURE 6
Bibliographic coupling of the articles within the field of coral reefs in the South China Sea.

2013). Factors such as depth, ocean currents, environmental stress, and hydrographic barriers are recognized as key influences on coral reef biodiversity (Pin et al., 2001; Benayahu et al., 2004; Kool et al., 2011; Simister et al., 2012; Huang et al., 2015). Additionally, foundational work on the nutritional ecology of marine vertebrate herbivores and the identification of new taxa, primarily from coral reefs and tropical freshwater systems, has been reported (Choat and Clements, 1998; Matsuura, 2015).

Category D (highlighted in yellow in Figure 6) focuses on coral reef bathymetry and habitat monitoring, a field that has seen notable progress through the integration of multispectral remote sensing and machine learning. These advancements have addressed three key challenges: (1) overcoming data scarcity using ICESat-2/MODIS multi-sensor fusion (Hu et al., 2014; Ma et al., 2020); (2) improving depth retrieval accuracy by combining machine learning with physical models (Liu et al., 2019; Xu et al., 2021b; Wu et al., 2022); and (3) enhancing habitat monitoring reliability through multi-dimensional feature engineering (Zhou et al., 2018; Su et al., 2019). In addition, early studies in this field explored statistical algorithms and geochemical methods for mapping water depth and monitoring environmental conditions (Yang et al., 2013, 2015; Huang et al., 2017).

Research category E (highlighted in purple in Figure 6) primarily comprises studies on the mechanical and geotechnical behavior of coral sand. Wang Xinzhi is a pioneering researcher in this field, having published six of the top ten articles. His work addresses critical aspects such as bearing capacity (Wang et al., 2011, 2021), particle obstruction due to irregular grain geometries (Wang et al., 2019), shear characteristics (Wang et al., 2017a), and permeability (Wang et al., 2017b, 2018). Zhu Changqi has contributed two of the top ten articles, focusing on sedimentary evolution and identifying key parameters that control strength (Zhu et al., 2014; Chang-Qi et al., 2016). Additionally, recent studies have explored microscale sand mechanics and creep characteristics (Ye et al., 2022; Gao and Ye, 2023).

The five identified categories collectively serve the critical aims of addressing climate change and ensuring coral reef protection. Category A is dedicated to understanding the current multi-stressor impacts on coral reef ecosystems. In contrast, Category B utilizes coral reef records to reconstruct past environmental conditions, offering potential insights that can inform protective measures. Category C underscores the ecological significance of coral reefs through its focus on biodiversity. Providing foundational data for conservation, Category D investigates coral reef bathymetry and facilitates habitat monitoring. Lastly, Category E explores the unique mechanical and geotechnical characteristics of coral sand, advocating for its long-term viability in coastal construction due to its inherent resistance to erosion and degradation in saline and severe weather conditions (Hasan et al., 2024).

3.3.3 The analysis on keywords co-occurrence

The analysis of keyword frequency provides a basis for describing the research domain and the focus of the collected articles. After cleaning the keyword data, 2,179 unique keywords

TABLE 7 Highly cited articles within the main identified research categories.

Research category A: Multi-stressor impacts on coral reef ecosystems		Research category B: Coral reef archives of environmental change		Research category C: Multi-level biodiversity dynamics in coral reef ecosystems	
Reference	Article citation	Reference	Article citation	Reference	Article citation
(Murray et al., 2019)	630	(Montaggioni, 2005)	336	(Liu, 2013)	322
(Li et al., 2021)	238	(Goodkin et al., 2011)	80	(Morton and Blackmore, 2001)	279
(Lu et al., 2018)	227	(Wilson, 2008)	79	(Choat and Clements, 1998)	183
(Yu, 2012)	206	(Saha et al., 2016)	69	(Huang et al., 2015)	157
(Ding et al., 2019)	187	(Yu et al., 2004b)	67	(Kool et al., 2011)	114
(Hughes et al., 2013)	149	(Shao et al., 2017)	65	(Pin et al., 2001)	84
(Archana et al., 2018)	113	(Yu et al., 2004a)	60	(Benayahu et al., 2004)	82
(Herbeck et al., 2011)	113	(Nguyen et al., 2013)	59	(Matsuura, 2015)	72
(Dai et al., 2009)	107	(Pope and Terrell, 2008)	52	(Simister et al., 2012)	70
(Yao and Wang, 2021)	102	(Fan et al., 2020)	49	(McManus, 1994)	57

Research category D: Coral reef bathymetry and habitat monitoring		Research category E: Mechanical and geotechnical behavior of coral sand	
Reference	Article citation	Reference	Article citation
(Ma et al., 2020)	233	(Wang et al., 2011)	302
(Yang et al., 2013)	54	(Wang et al., 2019)	101
(Xu et al., 2021b)	52	(Wang et al., 2017b)	78
(Su et al., 2019)	46	(Wang et al., 2017a)	66
(Yang et al., 2015)	37	(Wang et al., 2021)	46
(Huang et al., 2017)	31	(Zhu et al., 2014)	46
(Zhou et al., 2018)	27	(Chang-Qi et al., 2016)	43
(Liu et al., 2019)	25	(Gao and Ye, 2023)	38
(Hu et al., 2014)	25	(Ye et al., 2022)	37
(Wu et al., 2022)	24	(Wang et al., 2018)	36

were identified, of which 112 appeared at least four times. A heat map of these 112 keywords, based on their frequencies, was generated using VOSviewer (Figure 7). Since South China Sea and coral reef were part of the search query, they appear significantly more frequently than other terms and are therefore excluded from Figure 7 to allow for a clearer analysis of the research domain. Beyond these terms, the most frequently occurring keywords are coral, climate change, and coral bleaching, aligning with the research categories identified through the bibliographic coupling analysis. To facilitate the identification of the most frequent terms, author keywords with more than ten occurrences are listed in Table 8.

Table 8 shows that most research has been conducted in the *Xisha Islands, Malaysia, the Nansha Islands, Hainan*, and *the northern South China Sea*. The primary research subjects are reflected in the keywords *coral*, *coral reef fish*, *Scleractinian coral*, *diversity* and *coral community*. The major research focus includes the negative impacts of *climate change*, *macroalgae* proliferation, *sea level rise*, and *global warming*, with *coral bleaching* identified as the most pressing issue. Regarding research methods, *remote sensing* emerges as the dominant approach. This technology enables detailed classification of complex reef benthic substrates and facilitates the investigation and assessment of coral reef health, driving significant progress in the field (Xu and Zhao, 2014). With rapid advancements in remote sensing data sources, spectral characteristics analysis, and recognition technologies, this method has gained increasing popularity. Its capacity for large-scale coverage and non-invasive monitoring makes it especially valuable for studying coral reef ecosystems (AlZayer et al., 2025; Huang et al., 2025; Liu et al., 2025).

3.3.4 Text mining results: thematic conceptualization

The text mining analysis was conducted on the titles and abstracts of the collected peer-reviewed journal articles of our sample to uncover hidden semantic structures and research

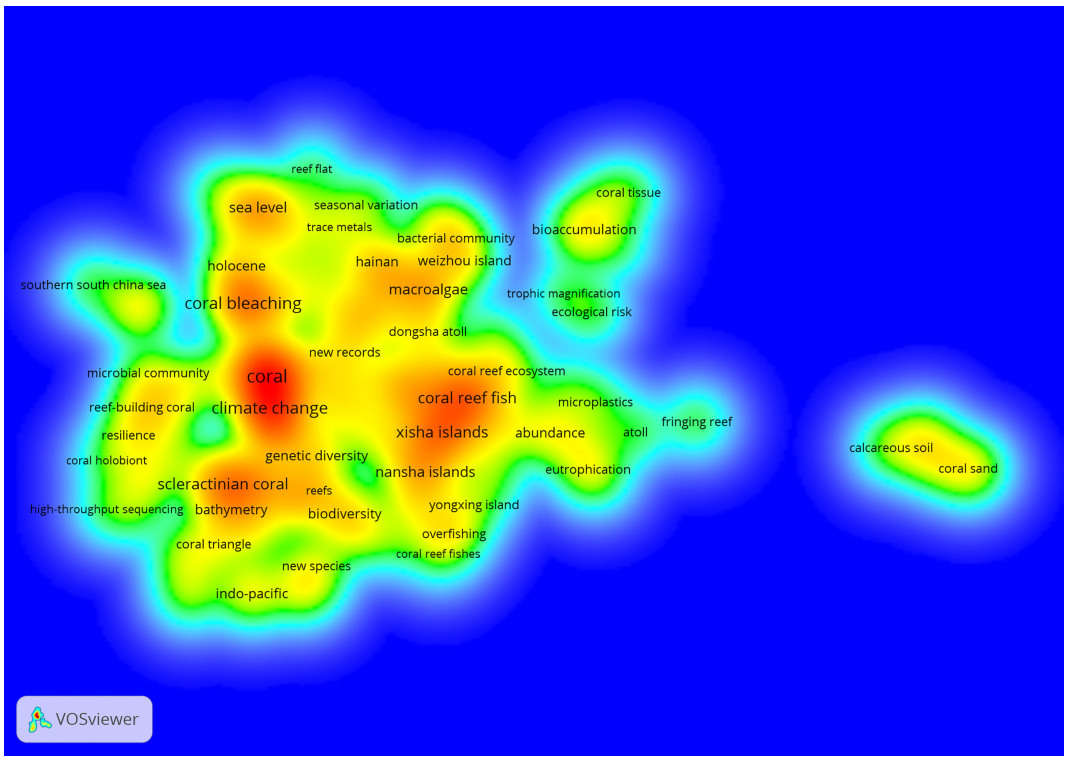

FIGURE 7
The density visualization map of author keywords within the articles in the research domain.

themes. After cleaning the data, 4134 unique noun phrases were identified. In order to base the analysis on the sufficiently frequent terms, a minimum of 5 occurrences was considered as a criterion for the selection of phrases, leading to the selection of 281 noun phrases. Then, the phrases were used to build clusters based on the co-occurrence of the terms to reveal the research themes of coral reef in the South China Sea. The 5 major theme identified includes (1) fundamental physical–biological interactions in reef systems, (2) biodiversity and symbiotic relationships in response to environmental stress, (3) climatic influences and the adaptive responses of reef systems, (4) conservation strategies and management practices for reef resilience, (5) remote sensing and algorithmic approaches for reef mapping and monitoring. Figure 8 presents the thematic structure of the coral reef research in the South China Sea. Similar to Figure 7, the size of the circles and the links between them show the occurrence of identified terms and their co-occurrence, respectively.

The first thematic cluster focuses on fundamental physical–biological interactions in reef systems (Cluster #1). Keywords central to this research theme include “coral reef”, “island”, “ocean”, “water”, “sediment”, “model”, “dynamics”, “fish”, “organic-matter”, “calcification”. These terms reflect the interplay

TABLE 8 The most frequent author keywords in the research domain.

Rank	Keyword	Frequency	Rank	Keyword	Frequency
1	Coral	34	8	Malaysia	13
2	Climate change	25		Sea level	13
3	Coral bleaching	23	9	Nansha islands	12
4	Coral reef fish	22	10	Bioaccumulation	11
5	Xisha islands	20		Coral community	11
6	Scleractinian coral	19		Global warming	11
7	Diversity	14		Hainan	11
	Remote sensing	14		Northern South China Sea	11
8	Macroalgae	13			

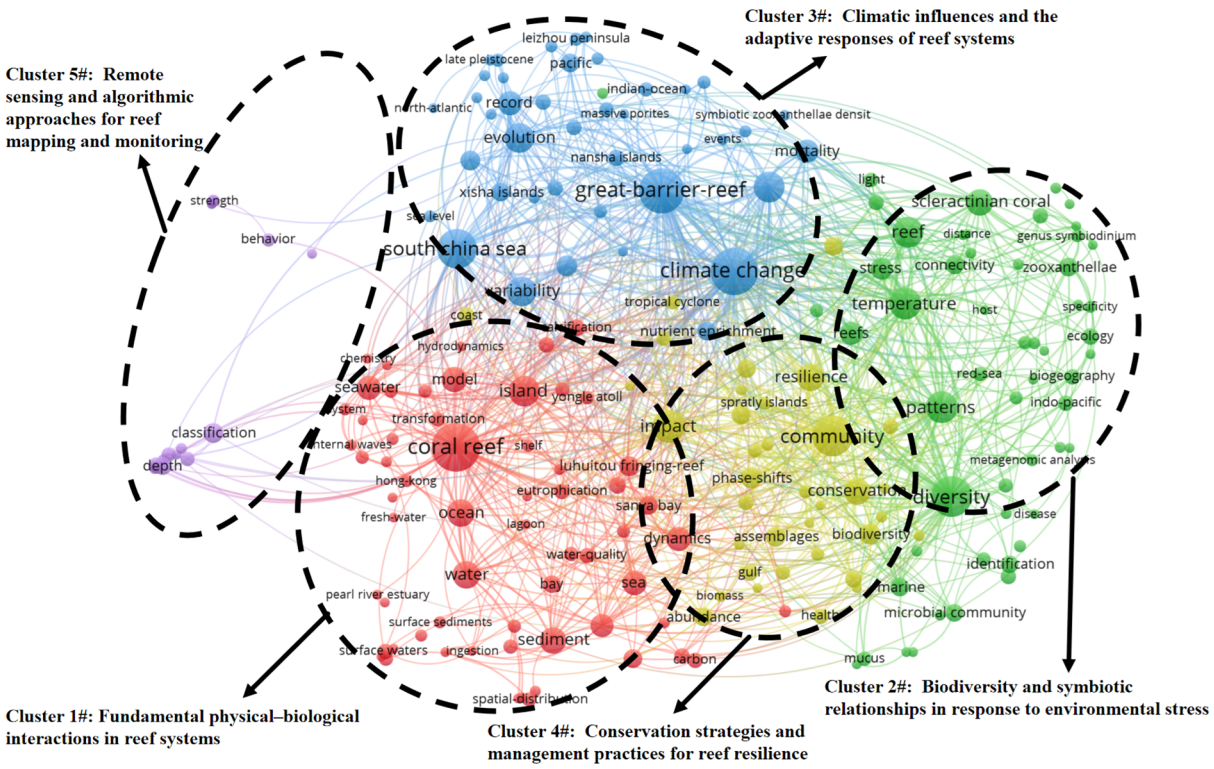

FIGURE 8
Major research themes in the field of coral reefs in the South China Sea.

between physical factors—such as ocean currents, water characteristics, and sediment movement—and biological processes, like fish populations, organic matter cycling, and calcification (Wilson, 2008; Xu et al., 2011; Shao et al., 2017; Zhang et al., 2021; Fan et al., 2024). Overfishing has been found in Nansha Islands and in the Malaysian South China Sea, which causes the "coral reef crisis" (Bell et al., 2006; Arai, 2015; Zhang et al., 2021). Parrotfish play a crucial regulatory role in coral reef ecosystems, and their susceptibility to fishing activities could lead to a gradual transition towards algal dominance, resulting in ecological phase shifts (Wang et al., 2024). Models play a critical role in examining these interactions, offering insights into reef dynamics across different scenarios (Melbourne-Thomas et al., 2011). This cluster highlights the combined impact of geophysical and ecological processes on coral reef development and function.

The second research theme (Cluster #2) concentrates on biodiversity and symbiotic relationships in response to environmental stress. It encompasses concepts such as "diversity", "patterns", "temperature", "reef", "stress", "zooxanthellae", "connectivity", and "microbial community". Research indicates that richness, rarity, and phylogenetic diversity vary significantly among reef areas in the South China Sea, and outcomes following projected extinctions cannot be predicted by species diversity alone (Huang et al., 2016). In the South China Sea, corals exhibit varying patterns of adaptability: those in the southern region are primarily threatened by thermal stress, while northern corals often suffer from severe anthropogenic disturbances (Qin et al., 2020). Moreover, rising ocean temperatures have been widely linked to coral reef bleaching, typically marked by the expulsion of symbiotic zooxanthellae, loss of zooxanthellae pigmentation, or both (Li et al., 2008). Coral-associated bacterial communities, which are essential for coral ecosystems and holobiont health (Yu et al., 2021), undergo substantial structural changes during bleaching events (Yang et al., 2021). Collectively, these findings demonstrate how biodiversity and symbiotic interactions influence coral reef responses to environmental challenges, offering vital insights for developing effective conservation strategies.

The third thematic cluster explores climatic influences and the adaptive responses of reef systems (Cluster #3). Key terms such as "climate change", "Great Barrier Reef", "growth", "variability", "evolution", "record", "mortality", and "ocean acidification" are central to this theme. Climate change affects coral reefs primarily through rising ocean temperatures and acidification, which may prevent some corals from surviving in tropical regions if they cannot adapt quickly enough (Yuan et al., 2019). Persistent seawater warming is recognized as a major threat to coral growth and reef development, with overall coral growth in the South China Sea projected to decline by the end of this century (Yan et al., 2019). The Great Barrier Reef, one of the most extensively studied coral reef systems, has provided research methodologies applicable to the South China Sea, such as the Foraminifera in Reef Assessment and Monitoring (FORAM) Index (A'ziz et al., 2021). Coral reefs in both

the South China Sea and the Great Barrier Reef are experiencing declines, with mortality patterns in the Nansha area resembling those observed in the central Great Barrier Reef (Yu et al., 2012).

Conservation strategies and management practices for reef resilience (Cluster #4) have emerged as a leading research focus. The key terms in this theme are "community", "impact", "resilience", "conservation", "biodiversity", "phase-shifts", "assemblages", "abundance", "management", "recovery", "responses", "coast", and "coral cover". Reefs in the South China Sea display spatial heterogeneity in resilience, recovery, and vulnerability to elevated water temperatures, as evidenced by variations in parameters such as coral cover and genus diversity. This variability necessitates targeted management interventions to guide reef rehabilitation for both biodiversity conservation and touristic development, involving relevant stakeholders (Vo et al., 2019). Notably, a phase shift from stony coral communities to alternative assemblages of octocorals and corallimorpharians has been observed in the South China Sea, attributed to outbreaks of crown-of-thorns starfish (Tkachenko et al., 2022). Reef restoration is recognized as an essential intervention to mitigate degradation. Moreover, these efforts have increased coastal community awareness of reef management and provided opportunities for active local participation and ownership (Chou et al., 2009).

The final thematic cluster highlights the application of remote sensing techniques and algorithmic approaches in reef mapping and monitoring (Cluster #5). Keywords associated with this research focus include "classification," "depth," "bathymetry," "imagery," "behavior," "shallow waters," "strength," and "algorithm." Shallow water depth estimation using multispectral imagery has become a vital method for marine surveying and mapping. To derive accurate bathymetric data, various algorithms such as the Quasi-Analytical Algorithm and geomorphic segmentation have been employed (Huang et al., 2017; Cheng et al., 2023; Zuo et al., 2024). Bathymetric data further support coral cover classification, enabling detailed assessment and monitoring of reef ecosystems (Asner et al., 2017). These advancements contribute to improved reef conservation and management strategies by enhancing the accuracy and efficiency of reef mapping efforts.

4 Discussion

4.1 Reginal challenges of the coral reef research in the South China Sea

The South China Sea is a critical biodiversity hotspot, supporting extensive coral reef ecosystems vital to ecological stability and regional livelihoods. However, research efforts on these reefs are unevenly distributed among neighboring countries. China has demonstrated a long-term commitment to coral reef research and conservation, contributing 550 publications, which outpacing other nations, and hosting eight of the top ten publishing institutions. From the Ridge-to-Reef perspective, effective reef management and coral survival demand integrated land–sea planning (Carlson et al., 2019), highlighting the need for enhanced reginal cooperation.

Data sharing is severely constrained by geopolitical tensions and overlapping territorial claims, which disrupt collaborative research and data exchange. While regional frameworks like the UNEP East Asian Seas Regional Seas Program and the UNEP/GEF South China Sea Project exist (Kao et al., 2012), their voluntary nature limits their effectiveness, with data sharing often restricted to specific project datasets (Tuan and Pernetta, 2010). The lack of binding mechanisms further complicates cross-border cooperation.

The livelihoods and economic realities of coastal communities pose further barriers to cooperation. Research indicates that coral reef study efforts correlate positively with per capita GDP and negatively with coral species richness (Fisher et al., 2011), reflecting the impact of human activities on reef health. Anthropogenic pressures, including nutrient enrichment (Guo et al., 2019), sewage discharge (Liu et al., 2012), and destructive fishing practices (Arai, 2015), accelerate reef degradation. Conservation measures, such as stricter pollution controls and fishing regulations, often impose economic burdens on coastal communities, diminishing their willingness to engage in research or support regional initiatives.

In summary, limited data sharing and socio-economic pressures collectively undermine regional cooperation in coral reef research within the South China Sea. Addressing these issues requires robust data exchange frameworks and strategies that balance conservation goals with community welfare to ensure sustainable management of this critical ecosystem.

4.2 Framework of the coral reef research in the South China Sea

Coral reef research in the South China Sea is built on a clear and organized framework, as evidenced by the alignment of text mining and bibliographic coupling analyses. Text mining extracts key themes from titles and abstracts, while bibliographic coupling groups studies based on shared references. Together, they reveal a research plan that starts with basic studies of physical and biological processes, such as ocean currents, sediment transport, and calcification, that form the foundation of reef ecosystems.

The research then moves to examine biodiversity and the ecological responses of reefs to stress, focusing on symbiotic interactions and resilience at both the organism and ecosystem levels. Finally, it addresses broader environmental challenges, including ocean warming and acidification, which pose serious threats to reef stability.

This logical progression from basic mechanisms to large-scale environmental impacts demonstrates the integration of marine biology, ecology, and climatology. Building on this foundation, the research extends into applied areas that focus on community management and conservation strategies aimed at reducing reef degradation and promoting recovery. These practical efforts are further supported by remote sensing techniques that improve monitoring accuracy and guide conservation actions.

The consistency between text mining and bibliographic coupling confirms the reliability of these themes, ranging from fundamental processes to biodiversity, climate impacts, management, and technological applications. This systematic framework not only advances scientific knowledge but also offers practical solutions for long-term conservation in this environmentally critical region.

4.3 Future trends in coral reef research in the South China Sea

Future research on coral reefs in the South China Sea will likely focus on two main areas: understanding the impacts of climate change and using new technology for better monitoring and management. Rising temperatures and ocean acidification are causing more frequent bleaching events, reduced coral calcification, and shifts in species diversity (McClanahan et al., 2007; Anthony et al., 2008; Kwiatkowski et al., 2015). Research will aim to clarify these changes using local studies and global models, helping us predict how reefs will respond to different climate scenarios. This work not only advances our scientific understanding but also supports global efforts to reduce greenhouse gas emissions and protect marine areas.

At the same time, technological innovation is transforming how we study coral reefs. Advances in satellite imagery, drones, and underwater sensors, combined with artificial intelligence, now allow for high-resolution, real-time data collection over large areas (Mohamed et al., 2018; Kaloop et al., 2022; Li and Hsu, 2022). These tools enable automated assessments of reef health, early detection of bleaching, and precise mapping of habitat changes (Xu et al., 2020, 2021a; Kopecky et al., 2023; Ma et al., 2023; Veeranjaneyulu et al., 2024). As these technologies continue to improve, they will help shift reef monitoring from reactive measures to proactive management, ensuring that conservation efforts are timely and effective.

5 Conclusion

This study employed bibliometric analysis to systematically review coral reef research in the South China Sea, utilizing records from the Web of Science Core Collection. Our analysis revealed a comprehensive research framework encompassing foundational studies of physical and biological processes, investigations into biodiversity responses to environmental stress, assessments of climate change impacts, and the development of advanced remote sensing techniques for reef monitoring, reflecting a multidisciplinary approach to reef science. However, challenges such as restricted data exchange and socio-economic pressures on coastal communities impede regional collaboration and effective management. Looking forward, future research should prioritize understanding the impacts of climate change and advancing innovative monitoring technologies to support sustainable management practices. Ultimately, our findings emphasize the necessity of a unified regional strategy that transcends geopolitical boundaries by leveraging scientific collaboration to ensure the long-term preservation of the South China Sea's coral reefs.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

JC: Writing – review & editing, Writing – original draft. FT: Resources, Writing – original draft. HL: Writing – original draft, Supervision. BH: Visualization, Writing – review & editing. XL: Validation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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