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Review

Development Trends, Current Hotspots, and Research Frontiers of Oyster Reefs: A Bibliometric Analysis Based on CiteSpace

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Abstract: The ocean is the largest reservoir on Earth. With the scarcity of water resources, the destruction of the benign cycle of the marine ecosystem would seriously impact people's quality of life and health. Oyster reefs, the world's most endangered marine ecosystems, have been recognized as a global issue due to their numerous essential ecological functions and provision of various ecosystem services. As a result, interest in oyster reef research has been steadily increasing worldwide in recent decades. The goal of this study is to assess the knowledge structure, development trends, research hotspots, and frontier predictions of the global oyster reef research field. Based on 1051 articles selected from the Web of Science Core Collection from 1981 to 2022, this paper conducted a visual analysis of oyster reef ecosystems conservation, restoration, and management. Specifically, it examined research output characteristics, research cooperation networks, highly cited papers and core journals, and keywords. Results indicate a steady rise in research interest in oyster reefs over the past 40 years, with notable acceleration after 2014. Authoritative experts and high-impact organizations were also identified. This paper outlines habitat conservation and restoration, ecosystem services, and the impacts of climate change as the primary research hotspots and frontiers. This paper provides valuable guidance for scholars and regulators concerned about oyster reef conservation to conduct research on oyster reefs.

Keywords: oyster reef ecosystem; conservation; bibliometric analysis; CiteSpace; research development

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1. Introduction

Global climate change has a great impact on water resources. Strengthening the protection of water resources and the restoration of water ecological environment are the only ways to realize the harmonious development of man and nature. The ocean is the largest reservoir on Earth. The destruction of the marine ecosystems will seriously affect the quality of life and health of people. The whole ocean is a large ecosystem, including many different levels of marine ecosystems. Further, oyster reefs are among the most depleted marine ecosystems globally. According to Beck et al. [1], an estimated 85% of all oyster reefs globally have been lost. For example, the population size of the eastern oyster (*Crassostrea virginica*; a.k.a., American oyster) has declined in many estuaries throughout the mid-Atlantic and southeastern United States, including eastern North Carolina and the Chesapeake Bay, where populations have been reduced to 1–2% of their historic peaks approximately a century ago [2]. Historically, it took the Chesapeake Bay's large oyster population approximately 3.3 days to filter the entire bay's water, compared with nearly a year for existing populations after the 1980s [2].

Oyster reefs are reefs formed of layers of oysters attaching to one another and can represent massive aggregations. They are widely distributed in estuaries, bays, and lagoons in subtropical and temperate regions. Globally, oyster reefs are found in the European Union (e.g., the Wadden Sea), the USA (e.g., Chesapeake Bay), China (e.g., Bohai Bay), Australia (e.g., Port Phillip Bay), New Zealand (e.g., North Canterbury), Argentina (e.g., Golfo San Matías), Canada (e.g., Nootka Sound) and other places [3]. Oyster reefs are an essential type of marine habitat that provides a wide variety of ecosystem services, such as providing food, improving water clarity [4], facilitating denitrification [5], protecting shorelines [6], increasing landscape diversity [7,8], and providing habitats for marine life [9–11]. Therefore, because of their large impacts and ability to transform ecosystems, oysters are known as "ecosystem engineers" [12].

The severe degradation and loss of natural oyster reefs, caused by activities such as overharvesting, disease, habitat degradation [13], water pollution and coastal zone development, has been recognized as a global problem since scientists became aware of their important ecological function [1,14]. Due to the diversity and high values of ecosystem goods and services provided by oyster reefs, there has been increasing interest in oyster reef restoration in many regions of the world [15–17]. Early attention to oyster reef recovery was mainly in the USA, especially in the Gulf of Mexico and the East Coast. The species preferred for restoration in the USA has been *C. virginica* [18]. In addition to the USA, New Zealand, Australia, some European countries, and China have also researched and applied oyster reef restoration practices [3]. To provide ideas and basic information for the whole process of reef restoration project, Fitzsimons et al. [12] published shellfish reef restoration guidelines based on the latest global scientific research achievements and practical experience.

In recent years, people have begun to study the essential ecosystem services provided by oyster reefs [19,20]. Through assessing oyster reef ecosystem services can assist coastal managers in realigning management plans to maximize the benefits of oyster reef restoration efforts. In addition to the research on oyster reef restoration and ecosystem services, extensive work has been conducted on the effectiveness of oyster reefs in serving as coastal defense [21], the impact of global climate change on oyster reefs [22–24], the role of oyster reefs in coping with climate change [25,26] and other aspects. Oyster reef studies have also evolved from single-factor exploration to ecological function restoration, from restoring degraded habitats to focusing on habitat changes under the combined influence of climate change and human activities.

At present, there are a number of summaries and literature reviews of oyster reef research [27–31]. As examples of reviews in the field, each of these review articles has its specific emphasis, and each plays an important role in the in-depth exploration of specific research directions. However, a broad-scale understanding of the current research status, hotspots, and future development direction of oyster reefs is lacking. Therefore, it is necessary to carry out a systematic analysis that considers oyster reef research in general based on existing publications. In the face of the large quantity of studies related to oyster reefs, a sufficiently comprehensive and accurate analysis of this field can only be achieved through bibliometrics and a visual review combining quantitative and qualitative methods.

Bibliometrics is an objective and quantitative method of researching and analyzing data obtained from databases [32–36]. CiteSpace is an information visualization software that can be used to scientifically analyze literature and extract pertinent information [37]. According to the characteristics of literature data, this software can conduct analyses of citation networks, co-occurrence networks, and conduct literature coupling [38]. These analyses can show the evolution of hot topics, identify the impacts of landmark studies, and analyze the relationships among articles and references [39]. To date, CiteSpace has been used in many research fields, including microplastics [40,41], biochar [42,43], pesticides [44], sustainable urbanization [45], waste management [46], and others [47–49]. Based on the bibliometrics method, this paper applies the CiteSpace software to comprehensively sort the relevant literature on oyster reefs available in the core collection database of the Web of

Science. This effort will clearly and intuitively present an overview of oyster reefs research and identify research hotspots and describe the evolution of related topics, as well as identify future trends in this field. This information will provide a useful reference and invaluable insight for future oyster reefs research and conservation practices.

2. Methodology

2.1. Data Sources

The data were obtained from the Web of Science (WoS) Core Collection database.

Using "oyster reef*" or "oyster beds*" as search terms, a total of 1176 documents published between 1981 and 2022 were retrieved. These included various types of documents, such as articles, conference proceedings, review papers, conference abstracts, book chapters, news, briefings, etc., that have been published on oyster reefs. Among the bibliographic documents gathered, research articles made up the highest proportion. Therefore, the literature type "journal article" was selected to ensure the data source was high quality. Finally, 1051 articles were selected after the removal of duplicates. The documents were imported into the "marked list" of WoS. The selected studies were downloaded in plain text format with "full record and references included" and submitted to CiteSpace for bibliometric analysis.

2.2. Data Analysis

The CiteSpace software (6.1.R2) was used, which is a graphic tool based on the JAVA platform developed by Chaomei Chen of Drexel University, Philadelphia, PA, USA [37]. The scientometric variables considered in this study were: (1) trends in the number of published articles, (2) contributing countries, (3) institutions, (4) authors, (5) distribution and citation track of papers in various disciplines, (6) cited journals, (7) co-citation analysis of references, and (8) research hotspots and trends: through keywords co-occurrence analysis, keywords timeline analysis and burst keywords analysis.

Among them, co-citation analysis examines the citation relationships among publications to identify key publications (or core literature) that have significantly impacted the field of research [50]. The keyword analysis summarizes the most highly emphasized aspects of a study. The analysis of word frequency and the co-occurrence of keywords can objectively and accurately reflect research hotspots in specific fields [46]. The time-axis view of keyword changes can better reflect the distribution and evolution trend of hot topics in the research literature from the time dimension [51]. Combined with the burst words, to grasp the frontiers and trends of oyster reef research field.

3. Results

3.1. Distribution of Publications over the Years

With the 1051 selected publications, looking at the number of articles published each year during the studied period can provide an overview of the progress made in the field of oyster reef research. As illustrated in Figure 1, in the past 40 years, the number of articles published per year increased from 1 to 102 from 1981 in 2020. Generally, this field exhibited slow growth until the mid-1990s. And in the most recent decade, research related to oyster reefs has accelerated rapidly.

3.2. Analysis of Output Characteristics of Articles

3.2.1. Contributing Countries Analysis

The countries contributing the most scientific articles in this field were the USA (with 712 publications, 67.7% of the total) (Figure 2 and Table 1). And the USA was the earliest contributor to conduct oyster reef research (since 1981). Australia and the Netherlands were the second and third largest producers of research in this field, but they contributed significantly less than the USA with 85 and 52 publications, respectively. The next largest contributing countries to oyster reef publications were China (39) and England (36).

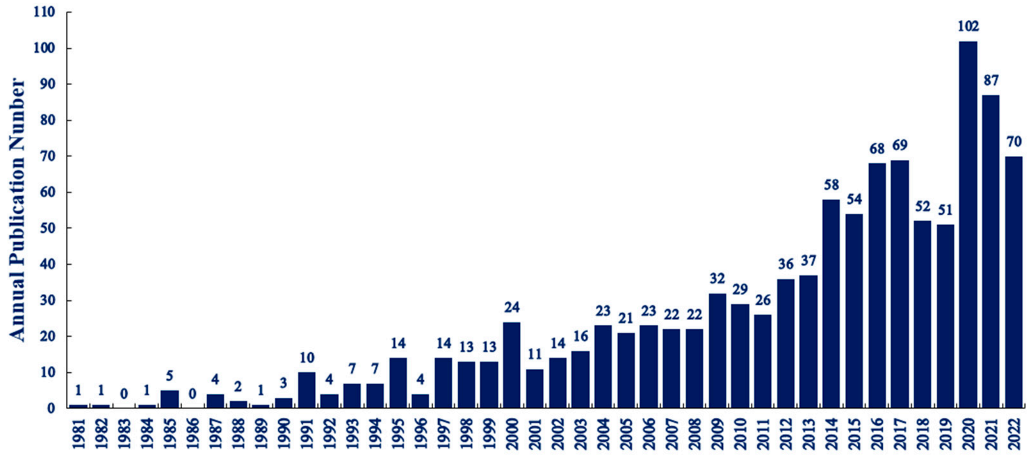

Figure 1. The annual number of published articles on oyster reefs extracted from the WoS Core Collection database.

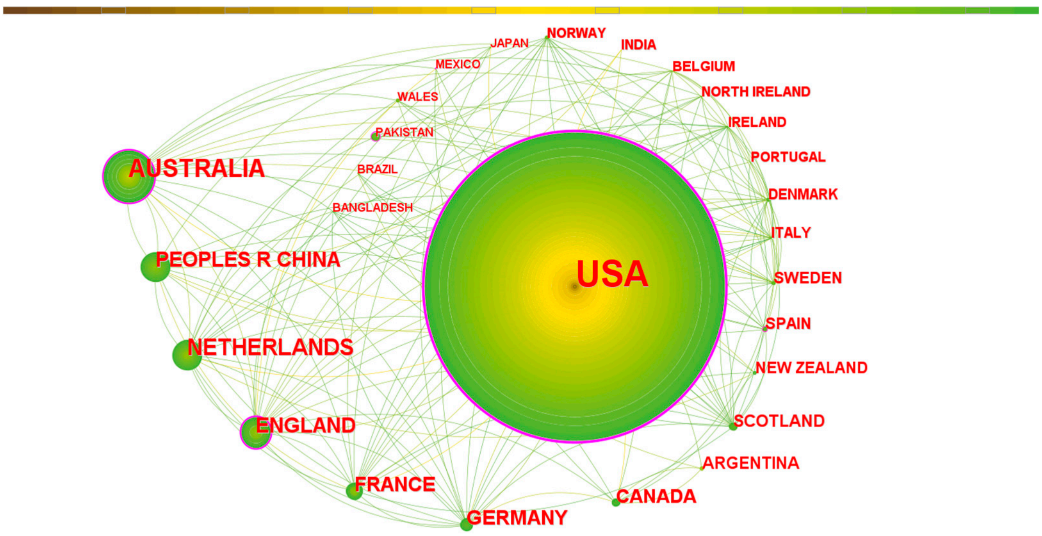

Figure 2. Contributions of various countries worldwide in the production of articles on oyster reefs. The subjects began in 1981, and the evolution until 2022 is shown from left to right.

Table 1. Top 10 contributing countries in terms of publications on oyster reefs. "Year" represents the time of the first appearance.

Rating	Country	Year [a]	Centrality [b]	Frequency	Average [c]	Contribution (%)
1	USA	1981	0.52	712	17	67.7
2	Australia	1999	0.23	85	4	8.1
3	Netherlands	1991	0.10	52	2	4.9
4	Peoples R China	2007	0.02	39	3	3.7
5	England	2006	0.26	36	2	3.4
6	France	1998	0.08	30	1	2.8
7	Germany	2003	0.02	30	2	2.8
8	Canada	1997	0.02	24	1	2.3
9	Argentina	2004	0.00	15	1	1.4
10	Scotland	2016	0.02	15	3	1.4

Notes: [a] "Year" represents the time of the first appearance. [b] Centrality: Betweenness centrality. [c] Average: The average number of publications per year, Average = Frequency/(2022 − Year) (keep the integers).

The nodes with purple outer rings in Figure 2 exhibit high betweenness centrality. Betweenness centrality is an indicator that reflects the size of the bridge role of a node in the network. When its centrality is greater than 0.1, it plays an important role in this field.

From the perspective of the centrality in Table 1, the USA exhibits the strongest centrality (0.52), followed by England (0.26) and Australia (0.23).

3.2.2. Institution Analysis

Network maps can help to identify influential institutions and establish connections among potential collaborators [40,52]. The institutions and cooperative relationships between them are shown in Figure 3. The nodes in Figure 3 represent individual research institutions. The larger the node, the greater the number of articles published by that institution, indicating a stronger academic influence on oyster reef research. The links between nodes reflect the cooperative relationships between research institutions. The more connections there are, the stronger the partnership between institutions.

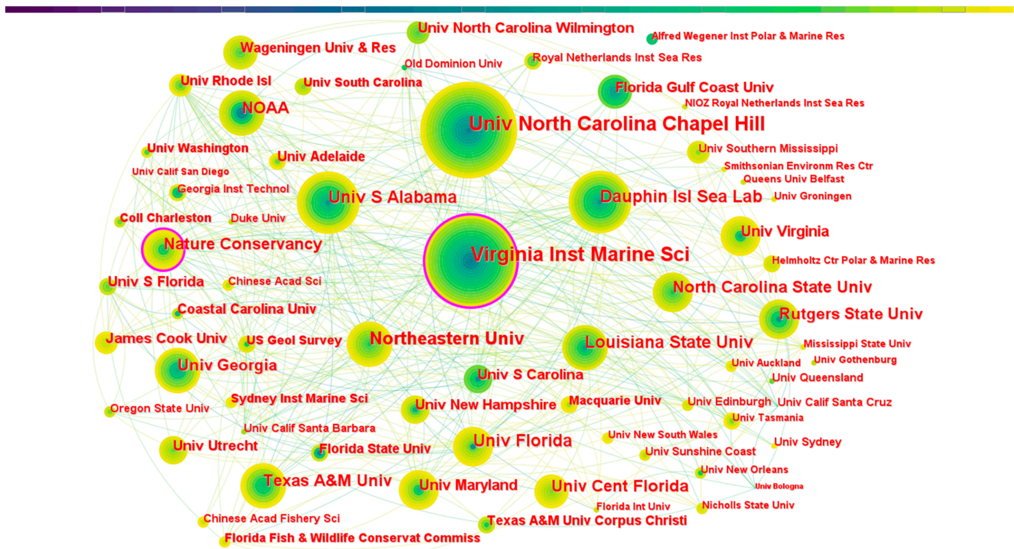

Figure 3. The network map of institutions for oyster reef research.

The Virginia Institute of Marine Science (VIMS) ranked first, with 67 related publications, accounting for 6.4% of all analyzed publications. The University of North Carolina at Chapel Hill was second (65 papers, 6.2%), followed by Northeastern University (40 papers, 3.8%). The next seven institutions were Louisiana State University, Dauphin Island Sea Lab, University of Florida, University of South Alabama, University of Central Florida, TNC, and North Carolina State University. The top 19 institutions in oyster reef research were all based in the USA. The 20th ranked institution was James Cook University, in Australia. This was consistent with the contributing countries analysis, which showed that the USA contributed more than half of all the articles.

Moreover, close collaborative relationships between these institutions were identified. VIMS and TNC each had close ties with 59 institutions, ranking them first in collaborations, followed by National Oceanic and Atmospheric Administration (NOAA) (58 institutions), University of North Carolina at Chapel Hill (55 institutions), and Dauphin Island Sea Lab (53 institutions).

Among all the institutions, only VIMS and TNC had betweenness centrality values exceeding 0.1 (purple outer ring, Figure 3), which indicated that they have played a significant bridging role amongst the collaborating entities producing oyster reef research. VIMS had a large literature quantity and a betweenness centrality of 0.14. VIMS, which is part of the College of William and Mary, has been a prominent institute in oceanography since its founding in 1940. It is considered among the oldest and largest oceanography schools in the USA. Furthermore, VIMS was also among the pioneering organizations in researching oyster reefs. In fact, the institute published its first article on oyster reefs in 1985.

TNC also had a relatively high centrality (0.12) in the network. TNC is among the world's largest nonprofit environmental organizations, founded in the USA in 1951. Like VIMS, the global headquarters of the TNC is located in Virginia. In addition to research articles, TNC has pioneered and conducted many works on oyster reef conservation and restoration, and on top of publishing the aforementioned Shellfish Reefs at Risk [53], Oyster Habitat Restoration Monitoring and Assessment Handbook [54], and Setting Objectives for Oyster Habitat Restoration Using Ecosystem Services: A Manager's Guide [55], they released the Restoration Guidelines for Shellfish Reefs in 2019 [12] and Research Report on Conservation and Restoration of Oyster Reef Habitats in China in 2022 [3], among others. In addition, TNC has contributed to relevant conservation and restoration activities in various countries, notably by leading or collaborating in more than 200 oyster reefs and other shellfish reef restoration projects worldwide [3], including in the USA, China, Australia, New Zealand, and Germany.

3.2.3. Author Analysis

Author analysis reveals the scientific publications contributed by individual researchers to this subject [47], as represented by nodes in Figure 4. In this figure, links indicate collaborations between authors.

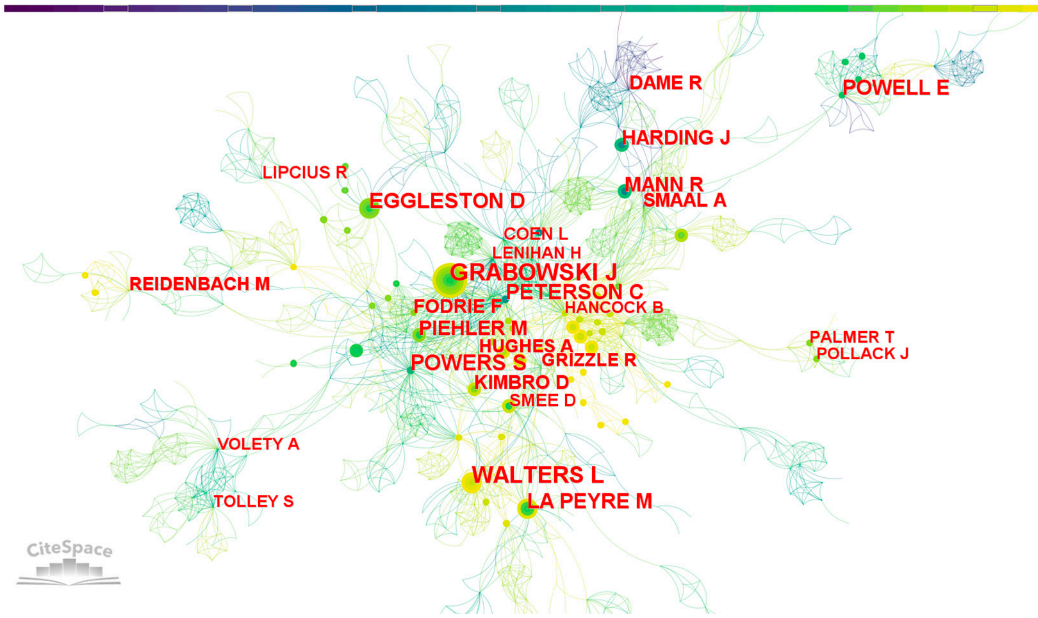

Figure 4. The network map of authors for scientific research on oyster reefs.

Table 2 lists the top ten contributing authors by the number of papers the author has published on oyster reefs, including detailed information and the countries they based in. Similar to institutional analysis, the top 10 publishing authors were from the USA. Among them, Jonathan H. Grabowski from Northeastern University, was the author with the most publications on oyster reefs.

3.2.4. Category and Disciplines

Figure 5 shows that oyster reef research has spanned several research disciplines, using a dual-map overlay designed by Chen and Leydesdorff [56]. The clusters of journals in different disciplines are shown using different colors. Depending on the global map of scientific research, the overall visualization of the dual-map overlay can reveal trends in the relevant scientific body of literature [41]. The colored curves in the graph represent reference paths, which clearly show the interdisciplinary relationships [57] within oyster reef research, with the citing journals map on the left and the cited journals map on the right. The stronger the connection, the thicker the line. Two dominant citation lines were present in the interdisciplinary relationships within oyster reef research, as shown by the two blue curves in Figure 5. Clearly, the citing journals were mainly distributed in disciplines labeled "Ecology, Earth, and Marine"; and the cited journals were mainly distributed in disciplines labeled "Earth, Geology, and Geophysics" and "Plant, Ecology, and Zoology". On the left side of Figure 5, the longer the horizontal axes of the ellipses, the more papers have been published in the corresponding journal. Through this analysis, this study showed that the literature on oyster reefs has been mainly published in journals in the marine biology, marine ecology, and earth fields.

Table 2. List of the top 10 contributing authors in terms of publications on oyster reefs including detailed information and their host countries.

Rating	Author	Country	Count	Year	Contribution (%)
1	Grabowski, J.H.	USA	34	2000	3.2
2	Walters, L.J.	USA	29	2002	2.8
3	Powers, S.P.	USA	24	2002	2.3
4	Eggleston, D.B.	USA	23	1998	2.2
5	Peterson, C.H.	USA	23	1998	2.2
6	Powell, E.N.	USA	19	1987	1.8
7	La Peyer, M.	USA	19	2005	1.8
8	Piehler, M.F.	USA	18	2011	1.7
9	Mann, R.	USA	18	1998	1.7
10	Harding, J.M.	USA	17	1999	1.6

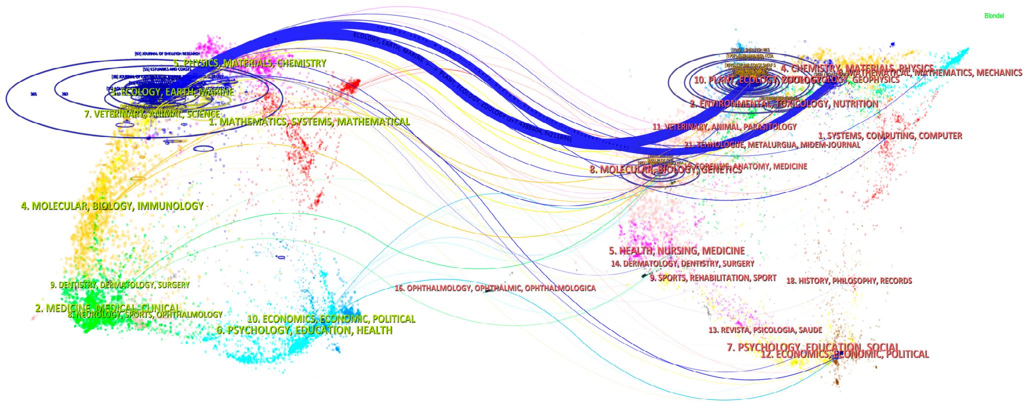

Figure 5. Dual-map overlays of oyster reefs research.

3.2.5. Core Journals Analysis

The top 10 journals with the most published oyster reef research articles, which accounted for 38.9% of the total, are shown in Table 3. Among them, "Journal of Shellfish Research" had the most publications related to oyster reefs (92 articles), accounting for 8.7% of the total. It was followed closely by "Marine Ecology Progress Series" and "Estuaries and Coasts" with 77 and 55 articles, respectively, accounting for 7.3% and 5.2%. "Journal of Shellfish Research", "Marine Ecology Progress Series" and "Estuaries and Coasts" are authoritative journals in the field of marine and freshwater biology, covering all aspects of marine ecology from fundamental ecological research to applications of ecological principles. Of all the 113 current marine and freshwater biology journals, these three rank 88th, 34th and 28th, respectively. Of the other top 10 journals, "Frontiers in Marine Science" was located in Q1 of the WoS-JCR partition (Q1 was the top 25% of the journals with the highest impact factor), and the other six journals were located in Q2 of the WoS-JCR partition. Based on the analysis above, it is evident that apart from the "Journal of Shellfish Research", the other nine journals are located in either Q1 or Q2 of the WoS-JCR partition, indicating their high influence within academia.

Table 3. Top 10 journals in the field of oyster reefs.

Rating	Citing Journal	Count	Contribution (%)	Impact Factor
1	Journal of Shellfish Research	92	8.7	1.218
2	Marine Ecology Progress Series	77	7.3	2.915
3	Estuaries and Coasts	55	5.2	3.032
4	Journal of Experimental Marine Biology and Ecology	38	3.6	2.476
5	PLoS ONE	31	2.9	3.752
6	Restoration Ecology	31	2.9	4.181
7	Frontiers in Marine Science	24	2.3	5.247
8	Estuarine Coastal and Shelf Science	23	2.2	3.229
9	Ecological Engineering	19	1.8	4.379
10	Journal of Sea Research	19	1.8	2.287

3.2.6. Most-Cited Journals Analysis

Variables regarding the number of citations linked to publications from each journal are shown in Figure 6 and Table 4. Regarding the citation count analysis, the journals "Marine Ecology Progress Series", "Journal of Experimental Marine Biology and Ecology", and "Journal of Shellfish Research" had frequencies of 788, 597, and 574, respectively. The next most-cited journals in oyster reef research were "Science", "Estuaries", "Ecology", "Estuarine Coastal and Shelf Science", "Marine Biology", "Bioscience", and "Estuarine Coastal". The journals with the highest centrality were "BioScience" (centrality = 0.14) and "Ecology" (centrality = 0.11). A cross-comparison with the co-cited literature analysis below revealed that the relative importance of BioScience was partially because two highly influential articles were published in this journal: "Oyster reefs at risk and recommendations for conservation, restoration, and management" [1] and "Economic valuation of ecosystem services provided by oyster reefs" [58].

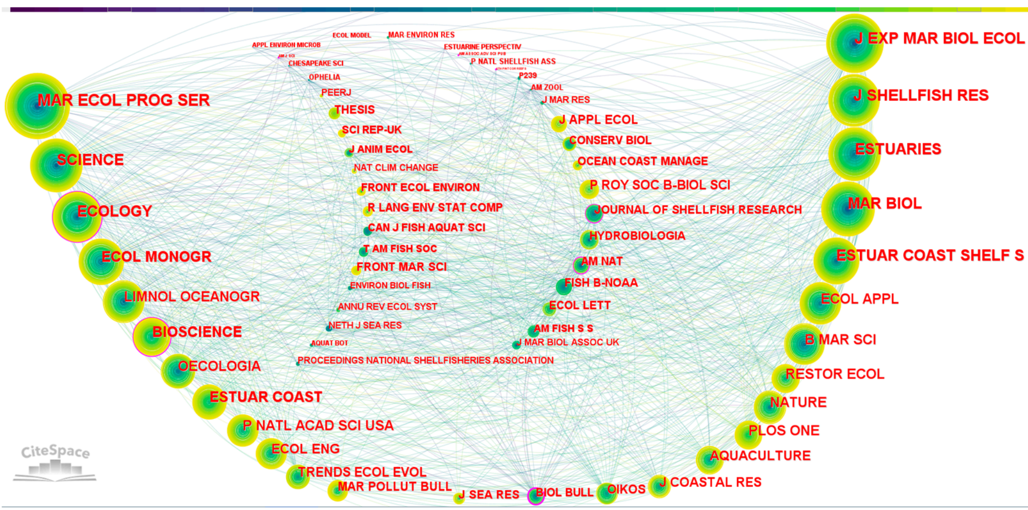

Figure 6. Journal co-citation network.

3.3. Co-Cited Analysis of References

The articles "Loss, status and trends for coastal marine habitats of Europe" (citations 750) [59], "Oyster reefs at risk and recommendations for conservation, restoration, and management" (citations 738) [1], and "How habitat degradation through fishery disturbance enhances impacts of hypoxia on oyster reefs" (citations 324) [60] were the top most cited articles. Table 5 presents a detailed analysis of the top 10 most cited publications from the WoS analysis. Notably, at the time of analysis, all articles listed in Table 5 had been cited more than 270 times. Michael W. Beck, Charles H. Peterson, and Jonathan H. Grabowski each authored three of the top 10 most cited articles. Among them, the article by Laura Airoldi and Michael W. Beck [59], which had been cited the most, mainly summarized the distribution and status of oyster reefs, historical losses and causes, trends and threats, and protection measures in Europe.

Table 4. Detailed information about the journals that received citations by the published documents collected for the present scientometric study on oyster reefs.

Rating	Cited Journal	Centrality	Frequency
1	Marine Ecology Progress Series	0.02	788
2	Journal of Experimental Marine Biology and Ecology	0.02	597
3	Journal of Shellfish Research	0.05	574
4	Science	0.03	510
5	Estuaries	0.05	483
6	Ecology	0.11	471
7	Estuarine Coastal and Shelf Science	0.04	467
8	Marine Biology	0.04	446
9	Bioscience	0.14	438
10	Estuarine Coastal	0.00	382

Table 5. Top 10 highly cited papers in the field of oyster reefs according to the WoS Core Collection database.

Rating	Title	Year	Author	Journal	Citations
1	Loss, status and trends for coastal marine habitats of Europe	2007	Airoldi, L. and Beck, M.W.	Oceanography and Marine Biology	750 [59]
2	Oyster Reefs at Risk and Recommendations for Conservation, Restoration, and Management	2011	Beck, M.W.; Brumbaugh, R.D.; Airoldi, L.; et al.	BioScience	738 [1]
3	How habitat degradation through fishery disturbance enhances impacts of hypoxia on oyster reefs	1998	Lenihan, H.S. and Peterson, C.H.	Ecological Applications	324 [60]
4	The cost and feasibility of marine coastal restoration	2016	Bayraktarov, E.; Saunders, M.I.; Abdullah, S.; et al.	Ecological Applications	322
5	Economic Valuation of Ecosystem Services Provided by Oyster Reefs	2012	Grabowski, J.H.; Brumbaugh, R.D.; Conrad, R.F.; et al.	BioScience	320 [58]
6	The role of ecosystems in coastal protection: Adapting to climate change and coastal hazards	2014	Spalding, M.D.; Ruffo, S.; Lacambra, C.; et al.	Ocean and Coastal Management	290
7	Epizootiology of Perkinsus marinus disease of oysters in Chesapeake Bay, with emphasis on data since 1985	1996	Burreson, E.M. and Calvo, L.M.R.	Journal of Shellfish Research	286
8	Habitat complexity disrupts predator-prey interactions but not the trophic cascade on oyster reefs	2004	Grabowski, J.H.	Ecology	284
9	Estimated enhancement of fish production resulting from restoring oyster reef habitat: quantitative valuation	2003	Peterson, C.H.; Grabowski, J.H. and Powers, S.P.	Marine Ecology Progress Series	284 [9]
10	Physical-biological coupling on oyster reefs: How habitat structure influences individual performance	1999	Lenihan, H.S.	Ecological Monographs	279

3.4. Keywords Co-Occurrence Analysis

Figure 7 and Table 6 show the co-occurrence of the collected keywords from the publications. In Figure 7, the node size represents the occurrence frequency of keywords, with larger nodes indicating higher frequencies. The analysis showed that keywords including "eastern oyster (*Crassostrea virginica*)", and "Chesapeake Bay" were the most frequently occurring of the keywords selected to represent the documents published on oyster reefs. This was followed by the keywords "restoration" and "habitat", which indicated a secondary focal topics of studies in this field. The only other keyword with a frequency exceeding 100 was "ecosystem service".

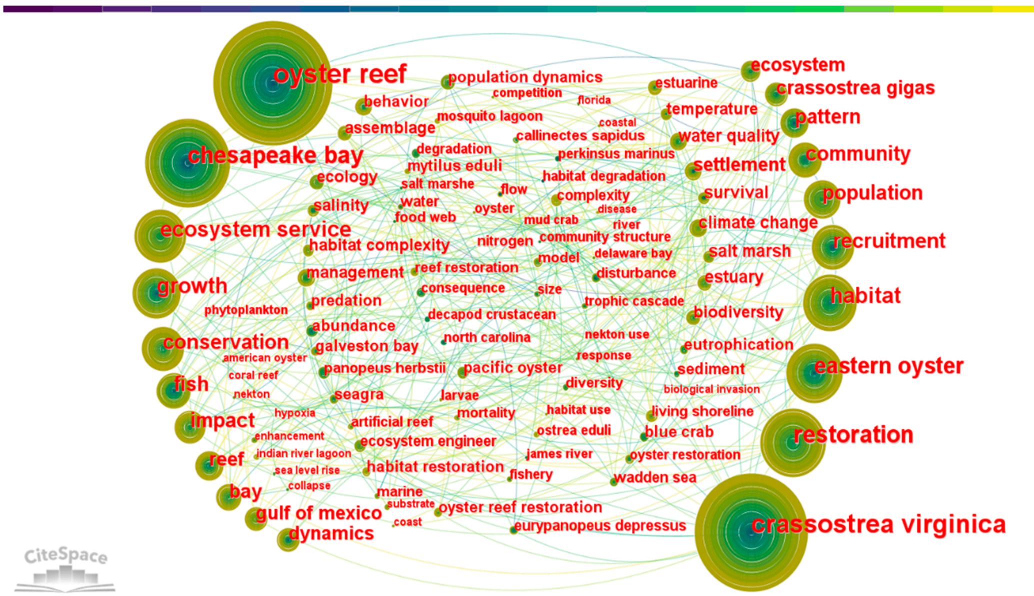

Figure 7. A schematic representation of network analysis of keywords appeared in scientific documents published on oyster reefs.

Table 6. The output of keywords co-occurring analysis and respective parameters of scientometric analysis. These keywords are most widely used to represent scientific documents published so far on oyster reefs.

Rating	Keyword	Centrality	Frequency	Year
1	oyster reef	0.03	293	1990
2	*Crassostrea virginica*	0.09	270	1992
3	Chesapeake Bay	0.09	169	1990
4	restoration	0.02	159	2003
5	eastern oyster	0.05	115	1996
6	habitat	0.05	106	1996
7	ecosystem service	0.05	101	2008
8	growth	0.01	93	1997
9	conservation	0.02	83	2002
10	recruitment	0.05	80	1991
11	population	0.04	71	1991
12	community	0.06	70	1991
13	fish	0.02	68	1996
14	impact	0.04	67	1999
15	pattern	0.01	57	1994
16	reef	0.02	54	1992
17	*Crassostrea gigas*	0.08	53	1992
18	bay	0.02	53	1999
19	settlement	0.03	46	1998

Table 6. *Cont.*

Rating	Keyword	Centrality	Frequency	Year
20	dynamics	0.08	46	1996
21	Gulf of Mexico	0.04	45	1997
22	ecosystem	0.04	42	1995
23	climate change	0.07	39	2004
24	estuary	0.03	39	1990
25	survival	0.03	37	2001

According to Figure 7 and Table 6, the keywords with frequent occurrence represent the research hotspots direction, specifically these are "habitat restoration" and "ecosystem services" of oyster reef. The research hotspot areas were mainly concentrated in the USA (Chesapeake Bay and the Gulf of Mexico). This was consistent with the previous analysis of contributing countries, in which the USA contributed more than half of all the examined articles.

3.5. Keywords Timeline Analysis

Figure 8 depicts the evolution of oyster reef studies in the temporal dimension, showing the changes in keywords throughout the timeline. The larger the node, the higher the frequency is. Nodes marked by purple circles have greater centrality (≥0.1). A link indicates that the keyword is related. The right side of the figure summarizes several important research clusters, named the Wadden Sea, *Crassostrea virginica*, ecosystem services and *Crassostrea gigas*, etc.

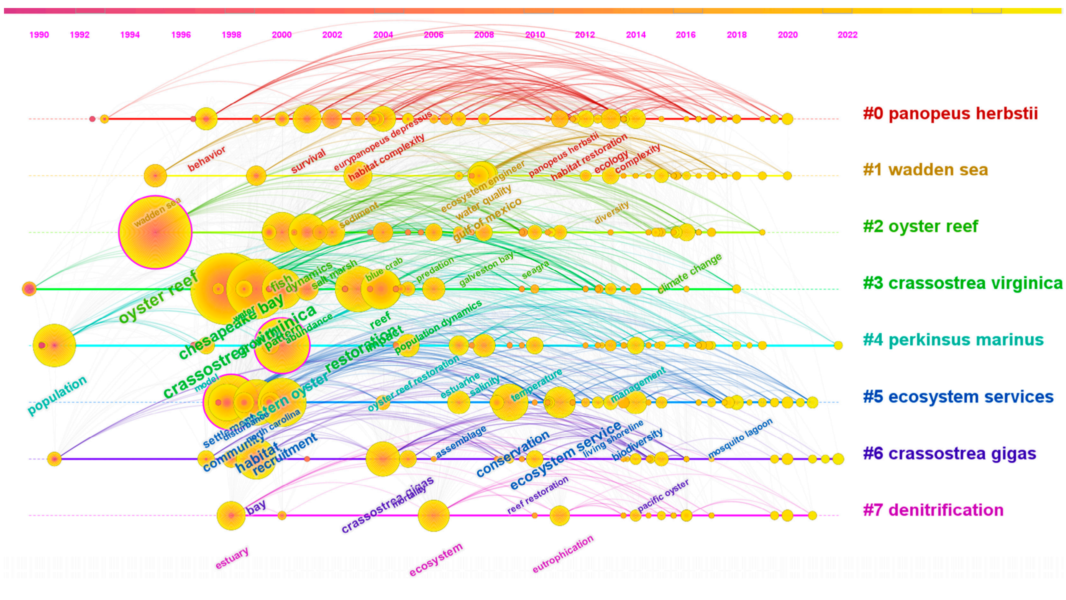

Figure 8. Visualization of keywords timeline analysis.

3.6. Burst Keywords Analysis

With the help of the citation burst function, we can find important keywords, that is, nodes where the number of keyword references suddenly rises or falls. In Figure 9, nodes with burst characteristics are filled in red, and the lengths of the red breakpoints reflect the duration, represented by "begin" and "end" [52]. The burst intensity is represented by the "strength" value. Large changes in the frequencies of keywords are identified as large bursts, which may indicate the novel frontiers in the field at different times. As shown in Figure 9, the top 10 keywords with the highest burst values were "restoration", "ecosystem service", "conservation", "climate change", "eastern oyster", "Chesapeake Bay", "habitat", "Gulf of Mexico", and "impact". Among them, "impact" was used mainly in regard to the impacts of important environmental factors, human activities, and invasive species on oyster reef communities or habitats, as well as the impacts of climate change on oyster species and the role of oyster reefs in responding to global climate change. From the overall distribution of these burst keywords in the relevant research on oyster reefs, it appeared that habitat conservation and restoration, ecosystem services, and the impact of climate change have attracted widespread attention and become priority research frontiers. Hot study areas were mainly focused around Chesapeake Bay and the Gulf of Mexico.

Figure 9. Top 30 keywords with the strongest citation bursts.

4. Discussion

4.1. Trends in the Number of Published Papers

Overall, the number of publications each year on oyster reefs exhibited an increasing trend, with especially large increases in recent years (Figure 1). This trend may be attributed to the relatively recent global consensus that oyster reef conservation and research will benefit ecosystems and economies worldwide. For example, the world's largest oyster reef restoration project in Chesapeake Bay started in the 1990s, contributing to the increase in relevant research in the coinciding period. Entering the 21st century, *Shellfish Reefs at Risk*, the first global review of the condition of oyster reefs was published [1,53], which was followed by shellfish reefs being added to the list of protected Wetlands at the Ramsar Convention on Wetlands in 2012 [12] and the publication of the Oyster Habitat Restoration Monitoring and Assessment Handbook [54] and Setting Objectives for Oyster Habitat Restoration Using Ecosystem Services: A Manager's Guide [55] by The Nature Conservancy (TNC) in 2014 and 2016, respectively. Oyster restoration in Europe, in contrast, is a new but fast-growing field. In order to best advance the practice of oyster restoration in Europe, the Native Oyster Restoration Alliance (NORA) was established in 2017. The NORA is a growing network of professionals seeking to exchange knowledge on the restoration of native oysters and native oyster habitats in European waters [61]. To date, there has been a much heavier emphasis in the scientific literature around oyster reef conservation and restoration worldwide.

4.2. Scientific Contributions

The most cited article by Laura Airoldi and Michael W. Beck [59], pointed out that oyster reefs may be among the most endangered marine habitats in Europe, with some of the largest impacts on oyster reefs coming from destructive fishing and overexploitation, with additional impacts from disease. Native oyster reefs were ecologically extinct by the 1950s along most European coastlines and well before that in many bays. Their article noted that the sustainable management of the few remaining fragments of native and semi-native coastal habitats in Europe should be prioritized. But perhaps the most cited fact about this article has to do with its broad scope. The article provides an overview of the distributions, historical losses, threats, and conservation measures of coastal habitats in the European gulf as well as estuarine and near-shore continental shelf environments. Furthermore, it covers a variety of coastal habitats in Europe, including coastal wetlands and salt marshes, oyster reefs, seagrass meadows, macroalgal beds, maerl beds, and sedimentary habitats (mudflats, sandflats, and subtidal soft bottoms).

The paper published by Beck et al. (2011) [1] was contributed to by experts from more than ten organizations in the USA, Italy, Uruguay, Australia, and China. They examined the condition of oyster reefs across 144 bays and 44 ecoregions. Overall, the study estimated that 85% of global oyster reefs had been lost. The authors also identified the most promising cost-effective solutions for oyster reef restoration. This article was the first global assessment of oyster reef survival, bringing global attention to this important coastal habitat. After publication, in 2012, shellfish reefs were added to the list of protected wetlands by the Ramsar Convention on Wetlands [12].

To explain the losses of oyster reefs, Lenihan et al. [60] did a series of surveys in the Neuse River estuary, North Carolina, USA. Their findings indicated that interaction between the degradation of reef habitats (height reductions) due to fishery disturbances and extended bottom-water hypoxic/anoxic conditions caused the observed mortality on natural oyster reefs. Interactions among environmental disturbances illustrate the need to use integrative approaches in ecosystem management to restore and sustain estuarine habitats.

The other highly cited articles mainly focus on the cost and feasibility of coastal restoration, the economic valuation of ecosystem services, the role of ecosystems in coastal protection, etc. These widely cited studies have played an important role in promoting the development of oyster reef research and conservation practices.

4.3. Research Hotspots in Oyster Reef

The research hotspots in the oyster reef field focus on oyster reef habitat conservation and restoration, oyster growth, causes of habitat degradation, and oyster reef ecosystem services.

Crassostrea virginica, the most common keyword, is a reef-building oyster species that has formed extensive intertidal oyster reefs in most estuaries and bays on the east coast of North America, from the mid-Atlantic states of the USA to the Gulf of Mexico and the Caribbean [61–63]. The next most common keyword was "Chesapeake Bay", which is a bay located in the middle of the east coast of the USA and is the largest bay in the USA. Historically, this bay has large populations of various oyster species, with *C. virginica* being most iconic.

The first regions in the world to initiate oyster reef restoration projects and related academic research were in the USA. These included locations across the U.S. Atlantic and Gulf coasts, especially in Chesapeake Bay [64–66] and the Gulf Coast [67–69]. From 1964 to 2018, 1,768 projects have been implemented, and since 2000, an average of 190 hectares of oyster reefs have been established each year in the USA [18]. Of the species used in restoration projects, *C. virginica* has predominated. In these projects, a variety of substrates have been used, including oyster shells, mixed oyster substrates, concrete and mixed concrete substrates, and others (e.g., limestone, granite, and surf clam shell) [70,71]. Through the implementation of many projects (generally large-scale with an average project size of 2.85 ha between 1999 and 2016) [18], practitioners have steadily increased the constructed reef area in Chesapeake Bay. As the number of oyster reef restoration projects has gradually increased, scholars have also begun to quantify important ecosystem services provided by oyster reefs in marine ecosystems, such as enhancing reef-generated shoreline stabilization, habitat provisioning, water-quality improvement services, etc. [68,71–73].

Currently, oyster reef ecological restoration has been carried out in coastal areas of the USA, Australia, some European countries, New Zealand, and China. For example, in 2020, China issued the Technical guideline for investigation and assessment of coastal ecosystem—Part 7: Oyster reef and the Technical guideline on coastal ecological rehabilitation for hazard mitigation—Part 6: Oyster reef, to provide technical support and a basis for the conservation and restoration of oyster reefs. Oyster reef restoration has become a hotspot in international marine ecological restoration research.

4.4. Hotspots Evolution and Research Frontiers in Oyster Reef

The first identified keyword was "nitrogen", which appeared in 1990 (Figure 9). Because in coastal ecosystems, nitrogen has been found to be the predominant limiting factor for primary producers. Nitrogen plays an important role in determining ecosystem function. Piehler et al. [74] found significantly higher rates of denitrification in structured habitats such as oyster reefs. Nitrogen removal by these habitats was found to be an important contributor to estuarine ecosystem function. Around 2000, the global consensus began to shift toward oyster reef conservation and research. Subsequently, "habitat degradation" became a hot topic from 2001 to 2007. In addition, "degradation" exhibited continued use with strong citation bursts from 2011 to 2015. During 2013–2022, a large number of research hotspots in the field of oyster reefs emerged and related studies increased in abundance. Since 2013, oyster reef "restoration" has attracted much attention and become a prominent research topic. This remains true to this day, with "restoration" being the keyword with the largest citation bursts and most abundant research achievements. Furthermore, in addition to Chesapeake Bay and the Gulf of Mexico, Mosquito Lagoon has emerged as a hot research area since 2018. A total of 27 articles were retrieved using "oyster reef*" and "Mosquito Lagoon" as search terms. For example, Locher et al. [75] studied the immediate (first-year) effects of restoration on sediment nutrients through a *Crassostrea virginica* restoration program conducted in Mosquito Lagoon, and Troast et al. [76] explored how fish communities responded in the first 12–24 mo following oyster reef restoration in Mosquito Lagoon. The focus species have been the eastern oyster (*Crassostrea virginica*) and Pacific oyster (*Crassostrea gigas*). In addition to the USA, in recent years, other countries have gradually conducted more research on oyster reefs, including Australia (mainly involving the Sydney rock oyster, *Saccostrea glomerata*), China (mainly in Bohai Bay), and some European countries (e.g., England, Germany, Netherlands, France, and Scotland; mainly involving the Wadden Sea). Along with restoration efforts, the attention paid to the ecosystem services provided by oyster reefs has increased since 2014, indeed "ecosystem service" became the keyword with second strongest burst intensity. Since 2016, under the influence of human activities and global climate change, oyster reef research has tended to diversify. In addition to research on oyster reef restoration and ecosystem services, the impact of global climate change on oyster reefs has become an important research hot topic [22–24], as has the role of oyster reefs in responding to global climate change [25,26]. Finally, "substrate" became a hot topic from 2018 to 2022. These keyword bursts illustrate how oyster reef conservation research has shifted through the years.

Looking at evolution of trends over time, it can be seen that oyster reef research has developed from single factor explorations to ecological function restoration, and from the restoration of habitats degraded by human activities to focusing on habitat restoration and development under the joint influences of climate change and human activities. As research has continually provided new insight into the ecological and economic importance of oyster reefs, recent research has increasingly focused on oyster reef conservation, restoration, and ecosystem services.

However, the research evaluating the effectiveness of oyster reef ecological restoration as a Nature-based Solution (NbS), including assessing oyster reef ecosystem services, the impacts of climate change on oyster reefs, the role of oyster reefs in responding to climate change, the effectiveness of oyster reefs as a coastal defense, and effective restoration plans, has not sufficiently matured. Additional and longer-term studies are needed on these topics in the future. For example, oyster reef ecosystem restoration, as a form of NbS, is seen as an increasingly important intervention strategy to counteract the degradation of coastal ecosystems and assist in climate change adaptation. Hynes et al. [77] pointed out that even if oyster reef restoration plans only consider the recreational use value and coastal protection services, without considering the value of many other additional ecosystem services, the benefit-cost ratios of oyster reef protection options always exceed one. But such approaches often face a variety of obstacles that can impede their development, such as the lack of knowledge at the local planner level [78]. However, Narayan et al. [21] also noted the lack of available evidence of wave attenuation by oyster reefs in their literature review focusing on the effectiveness of nature-based coastal defenses. Therefore, additional studies measuring the effectiveness of oyster reefs as a coastal defense are needed to provide a foundation on which to base project goals and set reasonable expectations.

While oyster reef restoration has had considerable success, many challenges remain. For example, restoration costs per unit area are high, the incidence of restoration failure is high, and the pressure imposed by climate change is increasing. Therefore, effective measures must be found to improve restoration efficiency and the resilience of reef ecosystems. Reeves et al. [28] suggested that identifying positive species interactions and systematically incorporating them into restoration practices could improve restoration success and enhance ecosystem services of restored oyster reefs. To do this, further research would be needed to understand the potential impacts of positive interactions and their applicability. Furthermore, Seavey et al. [79] pointed out that understanding the resilience of oyster reef communities to disturbances is key to developing effective conservation and restoration plans. Jiang et al. [17] showed that August was the most favorable window for capturing oyster spat via substratum additions to waters around natural reefs. Hernández et al. [18] pointed out that site characteristics, including access to adequate larval supply and elevation, greatly influence restoration success. Consequently, establishing longer-term, larger-scale, and standardized water-quality and oyster recruitment monitoring datasets to identify sites where restoration activities are likely to stimulate the recovery of self-sustaining, productive oyster reefs is an essential first step when designing projects that will yield positive return-on-investments. Moreover, in order to effectively enhance oyster reef protection and restoration, we must strengthen the academic knowledge in this field and transform practical experience into systematic and scientific guidelines. Furthermore, as pointed out by Draper et al. [80], global temperatures will continue to rise and warming will likely have a stronger impact on community dynamics in oyster reefs. Therefore, oyster reef restoration efforts should focus on accounting for climate change factors to maximize sustainability and success [81].

5. Conclusions

To sum up, the bibliometric analysis based on CiteSpace revealed the development trend, current hotspots and research frontiers of oyster reef research. Over the past 40 years, there has been a noticeable increase in publications on oyster reefs, indicating a growing interest in this subject. As an important coastal ecosystem, the oyster reef has many ecological functions such as providing habitats, purifying water, facilitating de-nitrification, and protecting coastlines. But they are also among the most degraded marine ecosystems and worth protection. Through the analysis of the cooperation network among countries, institutions and authors involved in oyster reef research, it can guide the direction of scientific research cooperation and help us select institutions, experts or journals accordingly.

The study on the keywords co-occurrence analysis, the keywords timeline analysis and the identification of burst keywords can provide new insights for the hotspots and trends in this field.

At present, the research of oyster reef shows a trend of diversification. Habitat conservation and restoration, oyster reef ecosystem services, impacts of climate change, biodiversity and selection of substrate are the latest frontiers of research in this field. However, at present, studies on issues such as carbon sequestration in oyster reef ecosystems, ecosystem services assessment and valuation, effectiveness assessments of oyster reef ecological restoration as an NbS, measurement of the effectiveness of oyster reefs as coastal defenses, impacts of global climate change on oyster reef habitat and the roles of oyster reefs in coping with climate change have not been in depth, which is worth further attention. In the future, systematic investigation and research on natural oyster reefs can be carried out. Taking oyster reef ecosystem restoration as an NbS will help realize win–win situations, where ecological protection and economic development both benefit from these natural habitats.

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