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Climate Change and Ocean Acidification: A Bibliometric Mapping of Scientific Literature

Loso Judijanto
IPOSS Jakarta, Indonesia and losojudijantobumn@gmail.com

ABSTRACT

Climate change and ocean acidification represent two of the most pressing and interconnected environmental challenges of the 21st century, with profound implications for marine ecosystems and global sustainability. This study conducts a comprehensive bibliometric analysis of scientific literature at the intersection of these two domains to uncover trends, collaborations, and thematic developments from 2000 to 2024. Using data retrieved from the Scopus database and analyzed with VOSviewer, we mapped co-authorship networks, keyword co-occurrence, temporal evolution, and country-level collaborations. The results reveal a dynamic shift in research focus—from early chemical and geophysical mechanisms to more recent explorations of ecosystem-level impacts, biological metabolism, and interdisciplinary approaches. Leading contributors include authors such as Caldeira, Doney, and Kroeker, with dominant research hubs located in the United States, United Kingdom, and Netherlands. The analysis also highlights growing international collaboration and identifies underrepresented regions and emerging topics that warrant further attention. This study contributes to the theoretical understanding of knowledge structuring in environmental science and provides practical insights for shaping future research agendas, fostering global cooperation, and aligning scientific inquiry with policy and conservation priorities.

Keywords: *Climate Change, Ocean Acidification, Bibliometric Analysis, VOSviewer, Scopus*

1. INTRODUCTION

Climate change represents one of the most pressing global challenges of the 21st century, driven primarily by the unprecedented rise in atmospheric greenhouse gas concentrations, chiefly carbon dioxide (CO_2), resulting from the combustion of fossil fuels, deforestation, and land-use changes. The Intergovernmental Panel on Climate Change (IPCC) Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) confirms that since 1970, the global ocean has absorbed more than 90 % of the excess heat in the climate system, with warming rates that have more than doubled since the early 1990s. These thermal changes, in combination with alterations in temperature, circulation, and chemistry, have profound implications for marine ecosystems and the services they provide [1]–[3].

Ocean acidification—the decline in ocean pH resulting from the uptake of anthropogenic CO_2—is increasingly recognized as the "other CO_2 problem" or the "evil twin of global warming". Since the industrial era, the surface ocean has taken up roughly 30 % of anthropogenic CO_2 emissions, causing reductions in carbonate ion concentration and saturation states, thereby decreasing the availability of material essential for calcifying organisms such as corals, molluscs, and foraminifera. This rapid decline in pH is unprecedented in the last 300 million years, posing critical threats to marine biogeochemical stability and biodiversity [4], [5]. The combined effects of ocean acidification, warming, and deoxygenation—often referred to as climate change's "deadly trio"—have compounding impacts on marine life and ecosystem processes. For example, meta-analyses and mesocosm experiments demonstrate that these stressors together lead to catastrophic consequences across food webs, dramatically reducing calcification, growth, and survival in multiple species. In the Arctic, ocean acidification is accelerating more rapidly than in other ocean basins due to ice melt and freshwater dilution, threatening organisms such as pteropods—key prey items for higher trophic levels—with far-reaching ecological consequences [6]–[8].

Historical and iconic research highlights the urgency of the issue: since the Industrial Revolution, the vast amounts of CO_2 absorbed by the ocean have altered seawater chemistry so drastically that organisms with calcium carbonate shells—such as pteropods and corals—face dissolution and inhibited growth. Coral reefs, which support roughly 25 % of marine biodiversity and underpin coastal fisheries and tourism, are especially vulnerable; projections indicate they could cease to calcify and begin shrinking around 2075 unless emissions are curbed. More recent assessments further underscore that acidification, deoxygenation, and warming collectively degrade marine ecosystems and threaten biogeochemical balance [9].

Despite mounting scientific attention to both climate change and ocean acidification—and a growing body of bibliometric literature mapping these fields—no comprehensive study has yet integrated both domains in a singular bibliometric framework. Existing analyses either focus on generalized climate research or specialize solely on ocean acidification, leaving a gap in understanding how these two deeply interconnected phenomena co-evolve in the scientific literature. This fragmentation obscures interdisciplinary research trends, thematic interconnections, and collaborative networks that span both climate-change and ocean-acidification research domains, reducing the potential for coordinated, holistic insights. The objective of this study is to perform a bibliometric mapping of scientific literature at the intersection of climate change and ocean acidification.

2. METHODS

This study adopts a quantitative bibliometric approach to systematically analyze the scientific literature at the intersection of climate change and ocean acidification. Bibliometric analysis is a recognized method for evaluating the structure, trends, and dynamics of scientific research through quantitative indicators such as publication counts, citations, co-authorship, and keyword co-occurrence [10], [11]. The methodology is designed to capture the evolution of research themes, map scientific collaboration, and highlight intellectual structures within this interdisciplinary field. Bibliographic data were extracted from the Scopus database, known for its extensive coverage of peer-reviewed literature across disciplines. The search query combined controlled keywords and Boolean operators—specifically using terms such as "climate change" AND "ocean acidification"—within the title, abstract, and keywords fields. The search was limited to journal articles published between 2000 and 2024 to focus on contemporary developments while allowing for historical continuity.

After retrieval, the bibliographic metadata—including titles, authors, publication year, source titles, author affiliations, citations, keywords, and abstracts—were exported in CSV and RIS formats for further analysis. The core analytical tool used in this study is VOSviewer (version 1.6.20), a widely used software for constructing and visualizing bibliometric maps. VOSviewer enables the creation of co-authorship networks, citation networks, and keyword co-occurrence maps by transforming bibliometric data into visual clusters. Co-authorship analysis was conducted to reveal collaborative patterns among researchers, institutions, and countries, while citation analysis identified influential publications and intellectual foundations of the field. Keyword co-occurrence analysis was used to detect prevailing themes and topic clusters, revealing how research on climate change and ocean acidification is interconnected and evolving.

To ensure robustness, data cleaning was conducted prior to visualization. This involved standardizing author names, merging synonyms and variant spellings of keywords (e.g., “CO2” and “carbon dioxide”), and removing general terms with low discriminative power (e.g., “study” or “impact”). Only documents written in English were included, as non-English papers were relatively few and typically lacked full metadata. Thresholds for inclusion in the VOSviewer maps (e.g., minimum number of occurrences for keywords or citations) were determined based on data distribution to maintain visual clarity and analytical significance. The combination of descriptive analysis and network visualizations provides a comprehensive understanding of how scientific inquiry on climate change and ocean acidification is structured, where it is growing, and what areas remain underexplored.

3. RESULTS AND DISCUSSION

3.1 Keyword Co-Occurrence Analysis

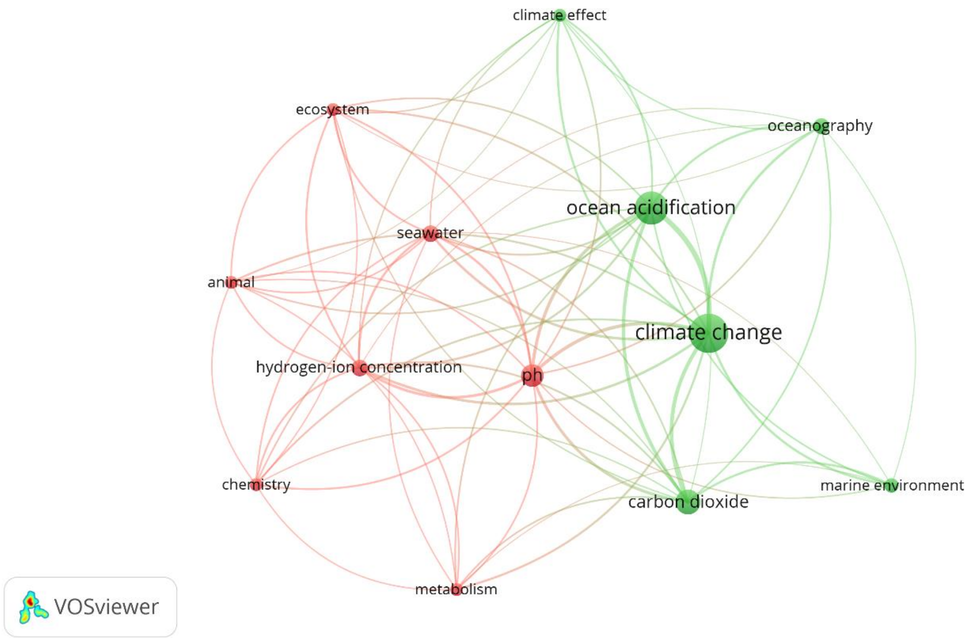

Figure 1. Network Visualization
Source: Data Analysis

Figure 1 reveals two dominant clusters indicated by distinct color coding: a green cluster centering around “climate change” and “ocean acidification,” and a red cluster orbiting around “pH” and chemical-biological terms such as “hydrogen-ion concentration,” “chemistry,” and “metabolism.” The green cluster primarily encompasses macro-scale environmental terms, highlighting themes such as "carbon dioxide," "marine environment," and "climate effect." This suggests that a substantial portion of the literature focuses on climate-driven macro-processes, atmospheric CO_2 accumulation, and broad ecosystem-level impacts, often through the lens of oceanography and environmental science. At the center of the green cluster are the keywords “climate change” and “ocean acidification,” which serve as conceptual hubs with high co-occurrence frequencies, evidenced by their large node sizes and multiple links. These terms are strongly linked to “carbon dioxide,” reflecting the direct causative chain in which increased atmospheric CO_2 leads to greater ocean uptake and acidification. The term “marine environment” is also prominently connected, indicating frequent studies that frame ocean acidification within broader marine ecosystem contexts. These connections show that climate change is often explored not in isolation, but alongside its chemical and ecological consequences, reinforcing the interdisciplinary nature of this domain.

In contrast, the red cluster is anchored by "pH" and "hydrogen-ion concentration," reflecting a strong emphasis on the chemical basis of ocean acidification. Supporting terms such as "seawater," "chemistry," "metabolism," and "animal" suggest a significant body of research investigating how pH alterations affect marine organisms at physiological and biochemical levels. For instance, changes in hydrogen ion concentration directly affect carbonate ion availability, thereby influencing calcification rates in marine organisms. The presence of the term "animal" indicates that this cluster also contains ecological and experimental research on the impact of acidification on marine fauna, possibly through lab- or field-based studies on calcifiers and metabolic stress. The network shows strong interconnections between the two clusters, suggesting that studies do not treat these themes in isolation. The bridge between "climate change" and "pH" is mediated through terms like "seawater," "carbon dioxide," and "ecosystem," which appear connected to both clusters. This implies a well-integrated research structure, where global climate phenomena and localized chemical-biological processes are increasingly studied in tandem. Moreover, the relatively central position of "ecosystem" highlights growing attention to system-level effects that blend atmospheric, chemical, and biological disciplines.

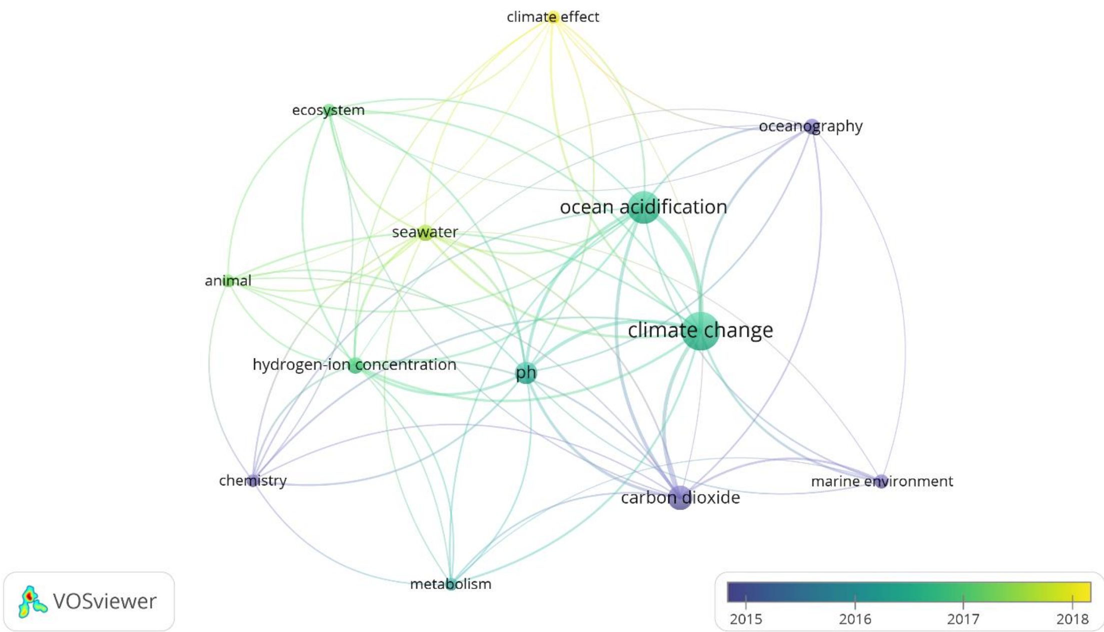

Figure 2. Overlay Visualization
Source: Data Analysis

The color gradient in this figure—from dark blue (older research, ~2015) to yellow (more recent, ~2018)—indicates the temporal evolution of key terms in the climate change and ocean acidification literature. Notably, core terms such as "climate change," "ocean acidification," and "pH" appear in greenish hues, suggesting sustained research attention across multiple years, with a moderate average publication year around 2016–2017. In contrast, terms like "climate effect" and "ecosystem" are depicted in yellow, indicating a relatively newer focus in the field. This shift signals a growing interest in evaluating the broader consequences of ocean acidification and climate stressors at ecosystem levels, particularly in the past five to seven year.

Terms such as "chemistry," "carbon dioxide," "marine environment," and "oceanography" are shown in dark blue, implying that these were foundational topics in earlier phases of research, predominantly prior to 2016. These terms reflect the initial scientific emphasis on the physicochemical mechanisms of acidification, oceanic CO_2 uptake, and the geophysical context of climate interactions. These foundational studies laid the groundwork for current explorations by explaining the carbon cycle, carbonate buffering systems, and their implications on ocean pH. The early concentration of research on these terms indicates a phase of disciplinary consolidation before expanding toward more integrative or applied topics.

Over time, the literature has shifted toward biological and ecological themes, as reflected in the more recent coloring of terms like “ecosystem,” “animal,” “metabolism,” and “climate effect.” These terms suggest an increasing emphasis on the biological consequences of ocean acidification, including how acid–base imbalances affect organism physiology, food webs, and ecosystem services. The term “seawater”, which connects older chemical terms with newer biological ones, appears in a transitional color (green-yellow), underscoring its role in linking chemical processes with ecological outcomes. Collectively, the overlay map shows a temporal progression from chemical mechanism studies (2015–2016) to impact- and consequence-focused research (2017–2018), marking the maturation and interdisciplinary expansion of the field.

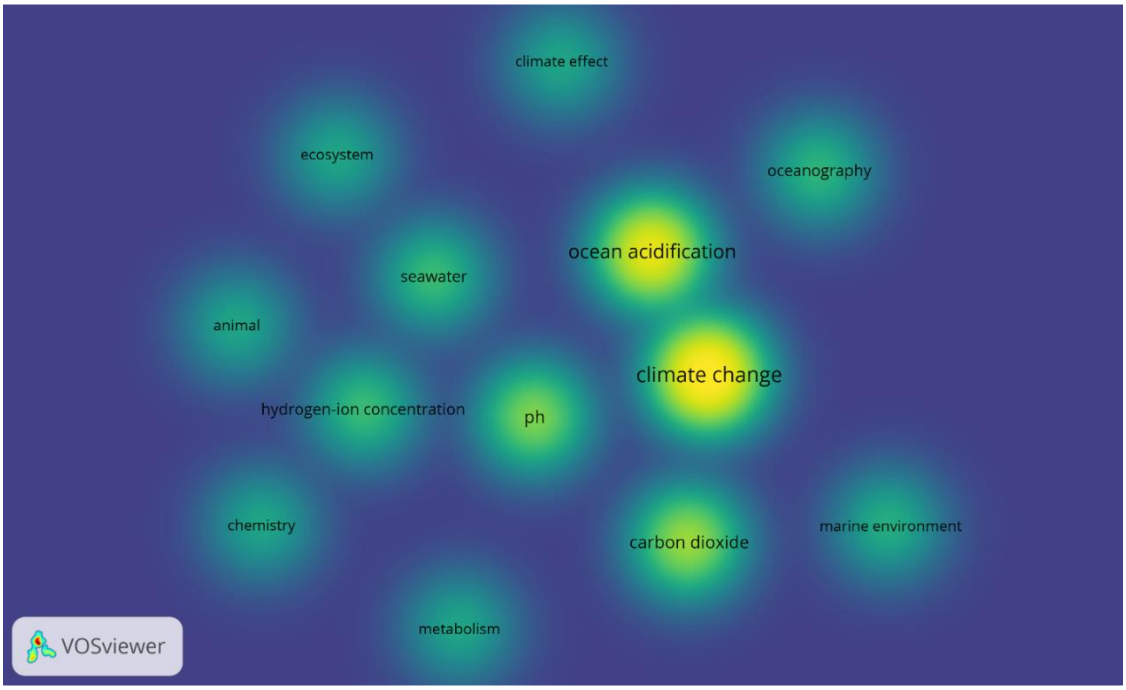

Figure 3. Density Visualization

Source: Data Analysis

The density visualization reveals the intensity and frequency of keyword co-occurrence within the scientific literature on climate change and ocean acidification. The terms "climate change," "ocean acidification," and "pH" are represented in the brightest yellow regions, indicating their central role and high occurrence across the dataset. These terms are at the core of the scholarly conversation, reflecting their conceptual importance and widespread integration in various studies. Their proximity also shows that research frequently links these topics together—emphasizing the chemical consequences of climate change, particularly the acidification process and its measurement through pH indicators. In contrast, surrounding terms such as “ecosystem,” “carbon dioxide,” “hydrogen-ion concentration,” “seawater,” and “marine environment” appear in green or light green zones, denoting moderate intensity and relevance. These keywords act as supportive or secondary concepts, showing that although they are important, they appear less frequently than the central terms. Peripheral terms like “animal,” “chemistry,” and “metabolism” are depicted in darker green to bluish tones, suggesting more specialized or niche areas of research.

4.2 Co-Authorship Visualization

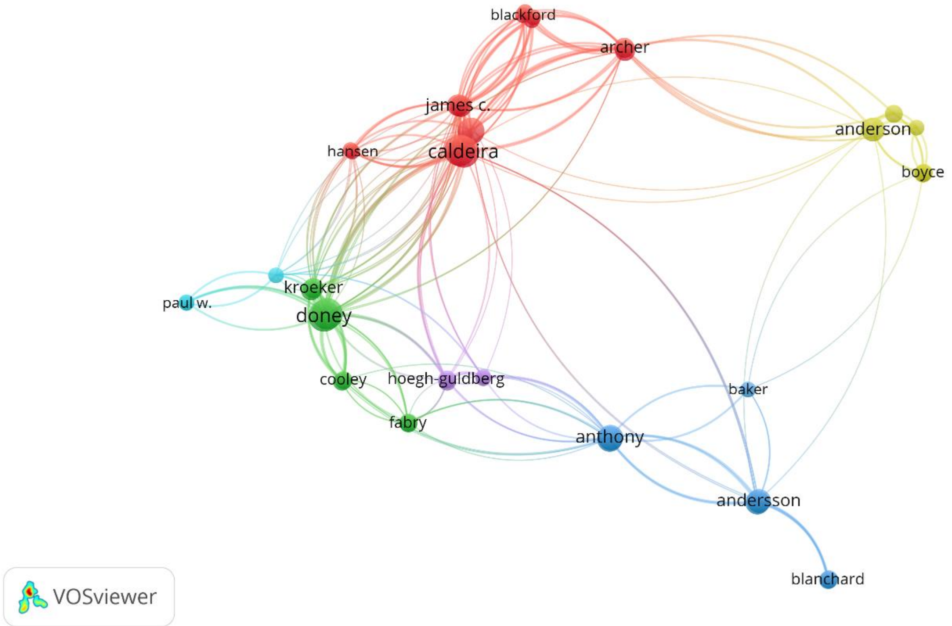

Figure 4. Author Visualization
Source: Data Analysis

Figure 4 displays a co-authorship network highlighting the collaborative relationships among prominent researchers in the field of climate change and ocean acidification. The network is divided into multiple color-coded clusters, each representing a distinct collaborative group. The red cluster, with Caldeira, James C.C., and Blackford at its core, indicates a highly interconnected group with frequent collaborations and strong scholarly influence. The green cluster features figures like Doney, Kroeker, and Fabry, suggesting another central group with ecological and biological research emphasis. Other notable clusters include the blue group (e.g., Anthony, Andersson, Baker) and the yellow cluster anchored by Anderson and Boyce, likely representing regional or disciplinary subfields. The density and direction of links indicate not just co-authorship frequency but also inter-cluster collaborations, highlighting the interdisciplinary and global nature of research in this domain. Authors like Caldeira and Doney serve as bridging figures who connect different research communities, suggesting their pivotal role in integrating chemical, ecological, and policy-driven studies.

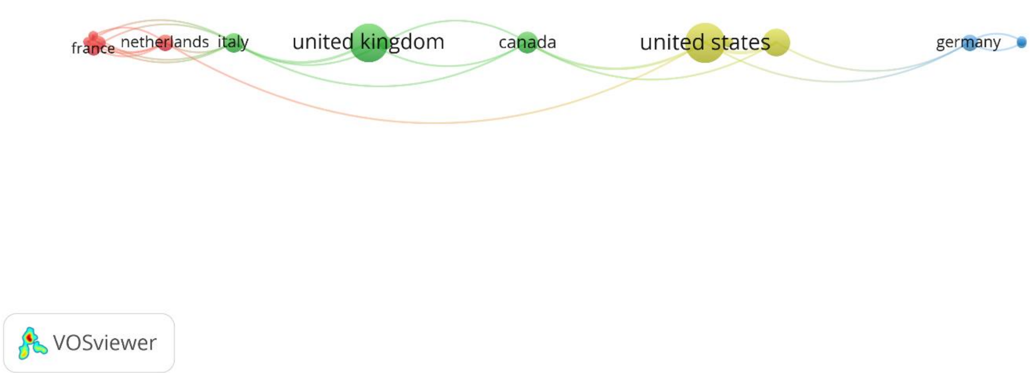

Figure 5. Country Visualization
Source: Data Analysis

Figure 5 ilustrates the global collaborative landscape in climate change and ocean acidification research. The United States, United Kingdom, and Netherlands emerge as key contributors with strong publication volume and broad international ties, indicated by their large node sizes and multiple linkages. The United Kingdom acts as a central hub, forming strong partnerships with countries such as Italy, Canada, and the United States, reflecting its strategic role in transatlantic and European scientific collaboration. The United States also maintains significant bilateral co-authorships, particularly with Germany, Canada, and the United Kingdom. Meanwhile, France and the Netherlands show dense regional collaborations within Europe. Although Germany is positioned at the periphery, its connection to the US and UK indicates targeted participation in high-impact research.

4.3 Citation Analysis

Table 1. Top Cited Literature

Citations	Author	Title
4587	[12]	Coral reefs under rapid climate change and ocean acidification.
695	[1]	Climate change and ocean acidification effects on seagrasses and marine macroalgae
647	[13]	Coral reef ecosystems under climate change and ocean acidification
203	[14]	Polycentric systems and interacting planetary boundaries - Emerging governance of climate change-ocean acidification-marine biodiversity
200	[15]	MEDUSA-2.0: An intermediate complexity biogeochemical model of the marine carbon cycle for climate change and ocean acidification studies
161	[16]	Intrageneric variation in antipredator responses of coral reef fishes affected by ocean acidification: Implications for climate change projections on marine communities
142	[17]	Transgenerational acclimation of fishes to climate change and ocean acidification
108	[18]	Coral Reefs under Climate Change and Ocean Acidification: Challenges and Opportunities for Management and Policy
105	[4]	Effects of carbon dioxide and climate change on ocean acidification and carbonate mineral saturation
95	[2]	Climate change and ocean acidification-Interactions with aquatic toxicology

Source: Scopus Database

Practical Implications

The findings of this bibliometric study provide critical insights for policymakers, environmental organizations, and funding agencies. By identifying the most active countries, authors, institutions, and thematic clusters in the domain of climate change and ocean acidification, this research enables more targeted collaboration and resource allocation. For instance, recognizing the central role of the United Kingdom and the United States in global research networks can guide international partnerships and co-funding initiatives for marine climate resilience. Moreover, the evolving themes—such as growing attention to ecosystem impacts, animal physiology, and acidification effects on metabolism—signal where research support and environmental management strategies should be prioritized. This allows practitioners and NGOs to align conservation efforts with emerging scientific knowledge, such as implementing adaptive measures for vulnerable marine species or developing region-specific pH monitoring programs based on identified gaps in the literature.

Theoretical Contribution

This study advances the theoretical understanding of how knowledge is structured and evolves in the intersecting fields of climate science, marine chemistry, and environmental ecology. By using bibliometric mapping techniques—including co-authorship networks, keyword co-occurrence, and overlay visualization—it contributes to the growing literature on scientific knowledge production in interdisciplinary domains. The temporal mapping reveals a thematic transition from geochemical mechanisms to ecosystem-level and biotic impacts, thus validating the theoretical model of research maturation and specialization over time. Additionally, the analysis of authorship and country collaborations enhances theories related to scientific collaboration dynamics, especially in transdisciplinary and transnational contexts. This study also bridges theoretical perspectives from environmental systems science with bibliometric theory, offering a new lens to examine how complex, systemic issues like ocean acidification are reflected in scholarly discourse and institutional collaboration.

Limitations

While the study provides a comprehensive overview of research patterns, it is not without limitations. First, the reliance on a single database (Scopus) may exclude relevant articles indexed elsewhere, such as in Web of Science or regional repositories, potentially biasing the representation of non-English or developing-country contributions. Second, the choice of keywords and search strings may inadvertently omit literature that uses alternative terminology or synonyms, especially in niche subfields. Third, the bibliometric approach emphasizes quantitative patterns but does not capture qualitative dimensions such as research quality, theoretical depth, or policy relevance of the publications. Lastly, the dynamic nature of the field means that findings may quickly become outdated as new topics and collaborations emerge; thus, continuous updating and triangulation with qualitative reviews are recommended for deeper insight.

CONCLUSION

This bibliometric analysis offers a comprehensive overview of the scientific landscape surrounding climate change and ocean acidification, highlighting key contributors, evolving research themes, and collaborative structures. The findings reveal that scholarly attention has progressively shifted from foundational studies on chemical processes and carbon dynamics to more integrated themes involving ecosystem responses, biological impacts, and interdisciplinary frameworks. The central roles of countries like the United States and the United Kingdom, along with influential authors such as Caldeira and Doney, underscore the global and cooperative nature of this research domain. Furthermore, the visualization of co-authorship networks and keyword clusters provides a nuanced understanding of how knowledge is produced, shared, and developed over time. This study not only contributes to mapping scientific progress but also informs future directions by identifying underexplored areas and emerging hotspots. As ocean acidification and climate change continue to threaten marine systems, such bibliometric insights are essential for guiding research investments, policy agendas, and cross-border collaboration.

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