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Deep-Sea Exploration: A Bibliometric Analysis

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ABSTRACT

Deep-sea exploration represents one of the most dynamic frontiers in contemporary science, integrating oceanography, marine engineering, ecology, and resource management. This study conducts a bibliometric analysis to systematically evaluate the evolution, thematic structure, and collaboration networks within deep-sea exploration research between 1980 and 2025. Using the Scopus database and VOSviewer for analysis and visualization, the study identifies major research trends, key contributing countries and institutions, and emerging areas of innovation. The results indicate a clear shift from traditional oceanographic studies and environmental assessments toward technologically driven themes, such as autonomous underwater vehicles (AUVs), remotely operated vehicles (ROVs), robotics, and underwater imaging. International collaboration patterns reveal China, the United States, and Japan as central players, supported by extensive networks with European and Asian partners. Furthermore, the co-occurrence of industrial themes such as offshore oil production and underwater mineral resources reflects the growing intersection between scientific discovery and commercial applications. The study contributes to theoretical discussions on knowledge evolution and interdisciplinarity while offering practical implications for policymakers, funding agencies, and industry stakeholders to foster sustainable and collaborative approaches in deep-sea exploration. Limitations regarding database coverage and emerging theme visibility are acknowledged, with recommendations for future research employing mixed-method strategies.

Keywords: *Deep-Sea Exploration, Bibliometric Analysis, Autonomous Underwater Vehicles (Auvs), Remotely Operated Vehicles (Rovs), Oceanography.*

1. INTRODUCTION

Deep-sea exploration has long captured the imagination of scientists, policymakers, and the public due to its potential to unlock new knowledge about the Earth's least understood environments. The deep ocean, generally defined as waters below 200 meters, encompasses nearly 65% of the Earth's surface, yet remains vastly unexplored compared to terrestrial and shallow marine systems [1], [2]. Advances in marine technology, from remotely operated vehicles (ROVs) to autonomous underwater vehicles (AUVs), have enabled more systematic surveys of deep-sea ecosystems, seafloor morphology, and biogeochemical processes [3], [4]. These developments are particularly relevant in the context of global environmental change and resource scarcity, as the deep sea represents both a frontier for biodiversity discovery and a source of critical minerals.

Over the past two decades, research interest in deep-sea exploration has expanded significantly, encompassing topics such as deep-sea hydrothermal vents, cold seeps, abyssal plains, seamounts, and trenches. The discovery of unique ecosystems around hydrothermal vents in the late 1970s shifted paradigms about life's dependence on sunlight, revealing chemosynthetic communities that thrive in extreme conditions [5]. Such findings have profound implications for evolutionary biology, biotechnology, and astrobiology [6]. Additionally, the growing importance of deep-sea fisheries and mineral resources, such as polymetallic nodules and cobalt-rich crusts, has intensified academic and policy discussions regarding sustainable management of the seabed [7], [8]. These developments underscore the urgency of synthesizing scientific output to track thematic progress and gaps.

At the same time, the deep sea has emerged as a critical focus in global environmental governance. International frameworks, such as the United Nations Convention on the Law of the Sea (UNCLOS) and recent negotiations on the conservation and sustainable use of marine biodiversity in areas beyond national jurisdiction (BBNJ Agreement), emphasize the importance of evidence-based policies informed by scientific research [9], [10]. Scientific knowledge is thus not only instrumental for discovery but also pivotal for shaping regulations that balance resource exploitation with conservation. The growing interdisciplinary nature of deep-sea research, spanning oceanography, geology, ecology, engineering, and law, reflects the complexity of challenges in exploring and managing these ecosystems.

The development of bibliometric analysis as a methodological tool provides a systematic way to evaluate the evolution of research fields. Bibliometrics allows for the mapping of publication trends, co-authorship networks, citation patterns, and thematic clusters, thereby offering a panoramic view of scientific landscapes [11]. When applied to deep-sea exploration, bibliometric analysis can illuminate how the field has matured, identify dominant research themes, and highlight collaboration networks that drive innovation. Previous bibliometric studies in marine science have explored topics such as climate change impacts on coral reefs or fisheries management, but relatively few have focused specifically on the deep sea. This presents an opportunity to consolidate fragmented knowledge into a coherent narrative of scholarly development.

Deep-sea exploration has societal relevance beyond academic discourse. The ocean plays a vital role in regulating the Earth's climate and supporting ecosystem services critical to human well-being [12]–[14]. Emerging debates on deep-sea mining, biodiversity conservation, and marine biotechnology underscore the necessity of robust scientific evidence to guide decision-making. By synthesizing patterns in deep-sea research, scholars and policymakers can better anticipate technological trajectories, ecological risks, and ethical dilemmas. Thus, a bibliometric analysis of deep-sea exploration is timely, as it provides insights into both the scientific frontier and the socio-political contexts shaping its future.

Despite the increasing volume of publications on deep-sea exploration, there remains a lack of comprehensive evaluation of how the field has evolved, which themes dominate, and where research gaps persist. Existing studies often focus on narrow aspects, such as hydrothermal vents or mineral extraction, without offering a holistic view of the research landscape. This fragmentation makes it challenging for new researchers to position their work, for policymakers to access synthesized evidence, and for funders to identify strategic priorities. Moreover, the interdisciplinary nature of deep-sea exploration complicates efforts to trace the integration of knowledge across scientific domains. Without a systematic bibliometric study, the field risks uneven development, with certain areas over-researched while others remain neglected. This study aims to conduct a bibliometric analysis of deep-sea exploration literature to map the evolution of research, identify key themes, and highlight collaboration networks.

2. METHODS

This study employed a bibliometric approach to systematically map the research landscape of deep-sea exploration. Bibliometric analysis was chosen because it provides a structured and quantitative means to assess scientific output, collaboration, and thematic evolution across time [11]. By focusing on publication patterns and citation networks, bibliometric methods help reveal the intellectual structure of a field, highlight its most influential contributors, and identify emerging themes. This approach is particularly useful for deep-sea exploration, which is inherently multidisciplinary and involves a broad range of scientific perspectives, from oceanography and ecology to geology and technology development. The data for the analysis were retrieved from the Scopus database, which is widely recognized for its comprehensive coverage of peer-reviewed scientific publications. The search strategy incorporated keywords such as “deep-sea exploration,” “deep ocean,” “hydrothermal vents,” “deep-sea biodiversity,” and “seafloor mining.” The timespan of the analysis was set between 1980 and 2025 to capture the period of modern deep-sea research influenced by technological innovations. The inclusion criteria were limited to journal articles, reviews, and conference proceedings. After retrieving the data, records were exported in CSV format compatible with VOSviewer, ensuring consistency in subsequent analysis.

ll analyses were conducted exclusively using VOSviewer, a software tool designed for constructing and visualizing bibliometric networks [15]. VOSviewer was applied to perform co-authorship analysis, citation analysis, and keyword co-occurrence mapping. Through these techniques, the study visualized the most influential authors, institutions, and countries, as well as the main thematic clusters driving the evolution of deep-sea research. The network maps generated by VOSviewer provided both a macro-level view of the field’s development and micro-level insights into collaboration patterns and thematic interconnections.

3. RESULTS AND DISCUSSION

3.1 Co-Authorship Analysis

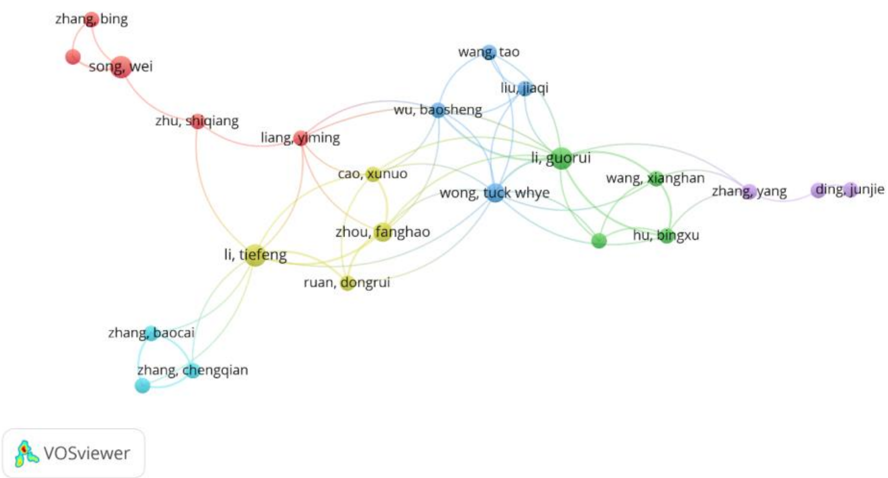

Figure 1. Author Visualization
Source: Data Analysis

Figure 1 illustrates a co-authorship network among scholars working in the domain of deep-sea exploration. Each node represents an author, while the connecting lines (edges) indicate collaborative relationships, with the thickness of the lines reflecting the strength of co-authorship links. The color clusters identify groups of researchers who tend to collaborate more closely with each other, highlighting distinct research communities within the field. For example, one cluster includes Zhang Bing, Song Wei, and Zhu Shiqiang, forming a tightly linked sub-network, while another is centered around Li Guorui, Wang Xianghan, and Hu Bingxu, indicating a different collaboration stream. Smaller but interconnected clusters, such as those of Zhang Baocai and Zhang Chengqian, further show the diversity of collaborative efforts. The network overall suggests that while multiple clusters exist, they are connected through bridging authors such as Wu Baosheng and Liang Yiming who act as intermediaries linking otherwise separate groups.

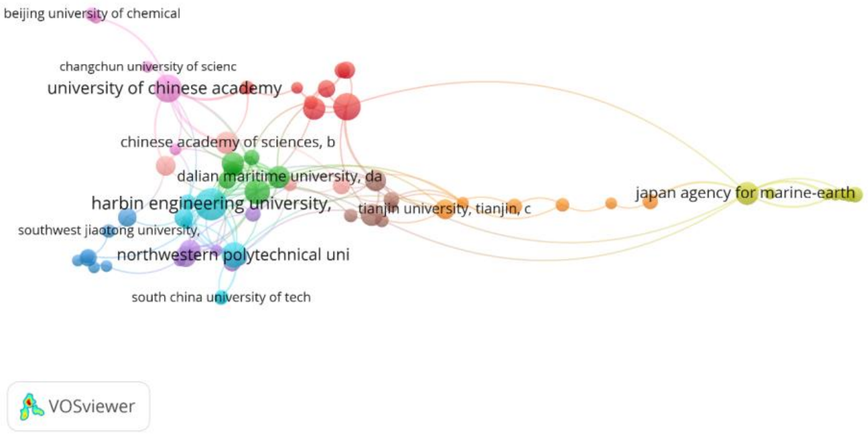

Figure 2. Affiliation Visualization
Source: Data Analysis

Figure 2 displays the institutional co-authorship network in deep-sea exploration research, highlighting the key academic and research organizations driving collaboration. The largest and most central cluster is dominated by the University of Chinese Academy of Sciences, Chinese Academy of Sciences, and Harbin Engineering University, which serve as hubs connecting multiple universities such as Dalian Maritime University, Northwestern Polytechnical University, and South China University of Technology. These dense interconnections suggest that China is playing a leading role in advancing research on deep-sea exploration. Another distinct cluster is represented by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), which appears more peripheral yet linked through cross-national collaborations with Chinese institutions. Smaller clusters, such as Beijing University of Chemical Technology and Changchun University of Science, contribute to specific subfields but are less connected to the broader network.

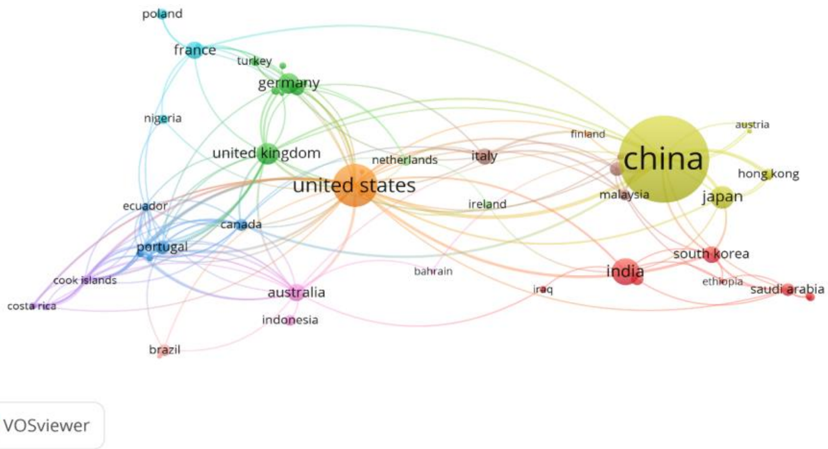

Figure 3. Country Visualization
Source: Data Analysis

Figure 3 highlights the global research network in deep-sea exploration, with China and the United States emerging as the two most dominant contributors. China forms the largest node, signifying its high publication output and extensive international partnerships, particularly with Japan, South Korea, Malaysia, and European countries. The United States, while slightly smaller, demonstrates strong cross-continental collaborations with the United Kingdom, Germany, France, Canada, and Australia, reflecting its longstanding leadership in ocean science. European nations, such as Germany, France, and Portugal, form a tightly interconnected cluster, often linking transatlantic research between North America and Europe. India and Saudi Arabia appear as growing contributors, forming regional alliances in Asia and the Middle East.

Keyword Co-Occurrence Analysis

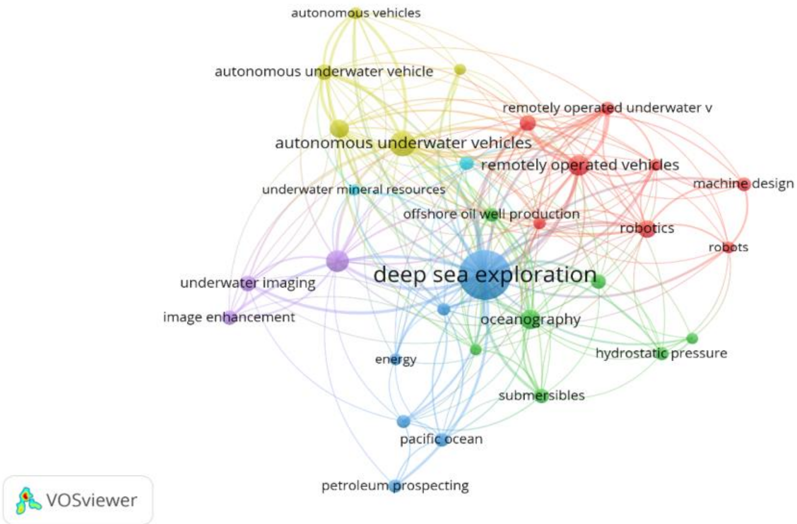

Figure 4. Network Visualization
Source: Data Analysis

Figure 4 provides an overview of the main research themes and emerging directions within the field of deep-sea exploration. At the center of the network, “deep sea exploration” acts as the dominant and most connected keyword, indicating its centrality as the anchor of the research domain. Closely associated terms include “oceanography,” “submersibles,” “hydrostatic pressure,” and “Pacific Ocean,” highlighting that the field is deeply rooted in marine science while simultaneously extending toward specific environmental and geographic contexts. The density of connections around these terms suggests that much of the scholarship is interdisciplinary, combining physical oceanography, engineering, and applied marine studies. One prominent thematic cluster focuses on technological innovation, represented by keywords such as “autonomous underwater vehicles (AUVs), remotely operated vehicles (ROVs), robotics, and machine design.” This reflects the increasing reliance on advanced technologies to probe extreme ocean depths where human access is limited. The strong interconnections between robotics, ROVs, and AUVs indicate that research is not siloed but instead oriented toward developing complementary technologies that expand exploration capacity. Such emphasis also underscores the rapid advancement of marine engineering and automation in recent years, pointing to a future where autonomous systems may dominate deep-sea missions.

Another cluster relates to resource exploration and industrial applications, with keywords such as “offshore oil well production,” “petroleum prospecting,” and “underwater mineral resources.” This stream of research reflects the economic interests in deep-sea environments, where energy and mineral extraction are seen as promising opportunities. The close links between these terms and core exploration concepts highlight the tension between scientific discovery and industrial exploitation. The map indicates that while resource-focused research remains significant, it is deeply intertwined with broader ecological and technological concerns, suggesting that sustainability and environmental risks are inherent parts of these discussions. The map also reveals an important focus on underwater imaging and data enhancement technologies, clustered around terms like "underwater imaging" and "image enhancement." These keywords point to efforts to improve data accuracy, visualization, and interpretation in extreme marine conditions, where low light, high pressure, and limited accessibility create substantial challenges. This research stream emphasizes the role of data science, imaging technologies, and sensor development as critical enablers of modern deep-sea exploration, allowing for higher-resolution mapping of seafloor topography, ecosystems, and geological features. The overall structure of the network shows the interconnectedness of scientific, technological, and industrial domains in deep-sea research. The convergence of robotics, energy, imaging, and oceanography around the core keyword demonstrates that deep-sea exploration is not limited to a single discipline but rather represents a multidisciplinary frontier. This integrated approach is crucial for addressing the dual goals of knowledge generation and responsible resource management.

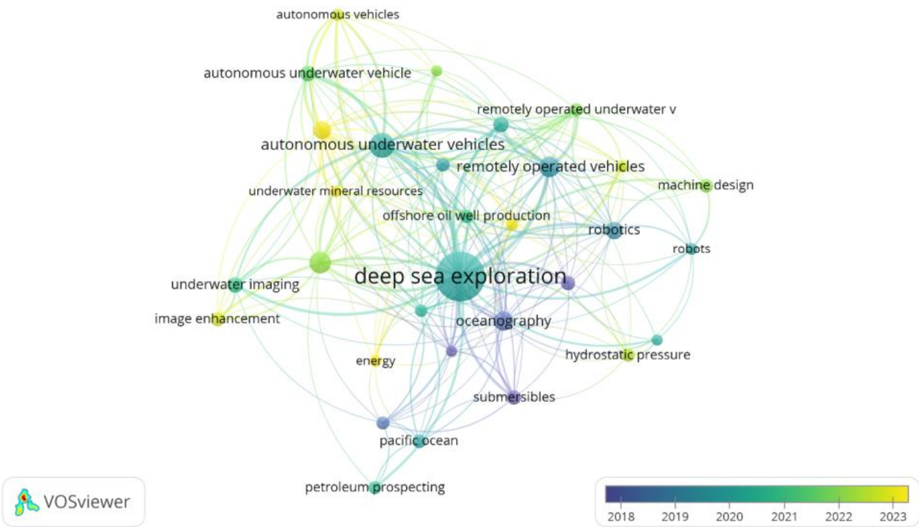

Figure 5. Overlay Visualization

Source: Data Analysis

Figure 5 highlights the temporal evolution of research themes in deep-sea exploration between 2018 and 2023. Earlier studies, represented in darker blue and purple shades, concentrated on foundational topics such as oceanography, hydrostatic pressure, submersibles, and the Pacific Ocean. These themes reflect the traditional scientific focus on understanding the deep-sea environment, its physical conditions, and geographic regions of interest. Such baseline knowledge provided the groundwork for subsequent advancements in technology-driven research and industrial applications. More recent studies, shown in green to yellow, indicate a shift toward technological innovation and industrial utilization. Keywords such as autonomous underwater vehicles (AUVs), remotely operated vehicles (ROVs), robotics, machine design, and underwater mineral resources have gained prominence since 2020. This transition illustrates how deep-sea exploration has increasingly embraced automation, engineering solutions, and resource prospecting, driven by the dual pressures of scientific curiosity and economic demand. The emergence of these terms in later years suggests that technology-enabled exploration is now at the forefront of the field.

At the same time, the presence of newer keywords like underwater imaging and image enhancement underscores the importance of data collection and visualization technologies for modern exploration. These areas have become crucial for addressing the challenges of observing and documenting deep-sea ecosystems in extreme conditions. Overall, the timeline of research reveals a progression from environmental and geographic studies toward engineering, automation, and applied industrial contexts. This reflects the growing interdisciplinary nature of the field and its responsiveness to global demands for knowledge, resources, and sustainable management strategies.

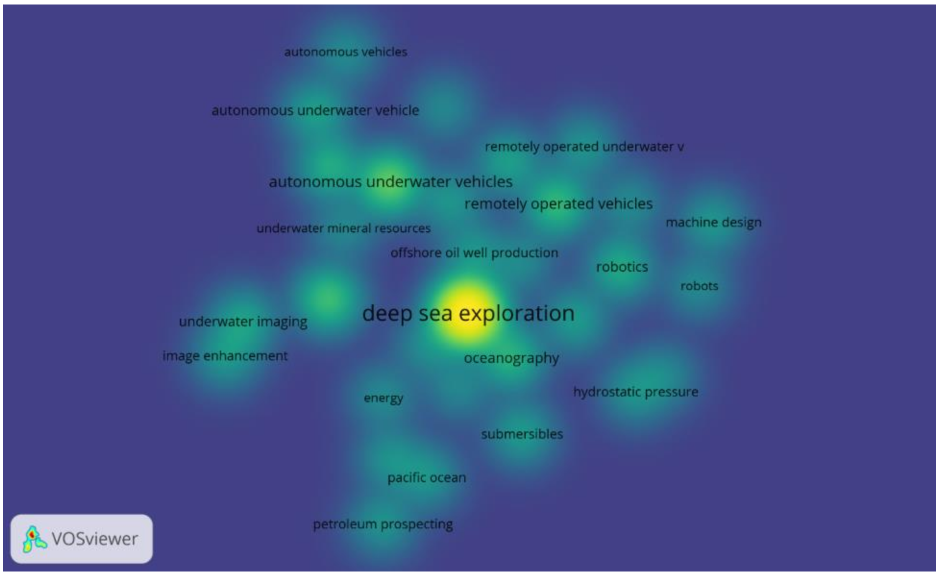

Figure 6. Density Visualization
Source: Data Analysis

Figure 6 highlights the core areas of research intensity within deep-sea exploration. The brightest yellow zone, centered on "deep sea exploration" and closely linked to "oceanography", shows that these remain the most central and frequently studied topics, forming the foundation of the field. Surrounding clusters in green, such as "autonomous underwater vehicles," "remotely operated vehicles," and "underwater imaging," indicate areas of high but slightly less central research activity. This suggests that while exploration and oceanographic studies dominate, technological advancements in robotics, imaging, and automation are increasingly critical drivers of the field. Meanwhile, less dense but still visible areas, such as "petroleum prospecting," "Pacific Ocean," "hydrostatic pressure," and "machine design," represent more specialized or applied research themes. Their peripheral positioning in the visualization shows that they are important but narrower in scope compared to the central cluster.

Practical Implication

The findings of this bibliometric analysis carry several important practical implications. First, the identification of research hotspots such as autonomous underwater vehicles, remotely operated vehicles, and underwater imaging provides clear guidance for policymakers and funding agencies in prioritizing technological innovation for deep-sea exploration. Governments and international organizations can use these insights to allocate resources toward areas that enhance both scientific discovery and sustainable exploitation of marine resources. Second, the mapping of international collaboration networks highlights the central role of countries such as China, the United States, and Japan, suggesting that future progress in deep-sea exploration will likely rely on strengthening multinational partnerships. This has direct implications for building shared infrastructures, data-sharing agreements, and cooperative governance frameworks under instruments like UNCLOS and the BBNJ Agreement. Third, the strong linkage between exploration and industrial themes, such as offshore oil production and mineral resources, signals to industry stakeholders the need for integrating sustainability measures and environmental safeguards into commercial ventures, ensuring that technological advances do not compromise ecological integrity.

Theoretical Contribution

From a theoretical standpoint, this study enriches the understanding of knowledge evolution and interdisciplinarity in the context of deep-sea exploration. By applying bibliometric analysis, the study demonstrates how scientific inquiry in this field has transitioned from foundational oceanographic studies toward a more technologically oriented and application-driven trajectory. This supports theories of scientific paradigm shifts [16] by illustrating how technological innovation can redefine research priorities and reshape disciplinary boundaries. Additionally, the mapping of co-authorship and institutional networks contributes to the literature on scientific collaboration theory, emphasizing the role of central actors and bridging institutions in fostering interdisciplinary integration. Finally, by connecting industrial, technological, and ecological domains, this study provides a conceptual foundation for extending the socio-ecological systems perspective to deep-sea research, highlighting how human activities, technological advancements, and environmental stewardship are tightly interlinked.

Limitation

Despite its contributions, this study has several limitations that should be acknowledged. First, the bibliometric analysis relied solely on the Scopus database, which, although comprehensive, may not capture all relevant publications indexed in other sources such as Web of Science or regional repositories. This may introduce bias toward journals with broader international visibility. Second, the reliance on keywords and author-supplied metadata means that some relevant research may have been excluded if it used alternative terminology not captured by the search strategy. Third, while VOSviewer provides powerful visualization of co-authorship, citation, and keyword networks, it does not assess the qualitative depth of research contributions, such as methodological rigor or policy relevance. Finally, bibliometric maps are inherently time-sensitive; emerging research themes may take several years to gain visibility in citation networks, which means that the most recent innovations may be underrepresented. These limitations suggest that future studies could adopt a mixed-method approach, combining bibliometrics with systematic literature reviews or expert interviews to provide a more nuanced understanding of deep-sea exploration research.

CONCLUSION

This study provides a systematic bibliometric analysis of deep-sea exploration research, revealing the intellectual structure, thematic evolution, and collaboration dynamics that have shaped the field over the past four decades. The findings demonstrate that deep-sea exploration has progressed from traditional oceanographic and environmental studies toward a technology-driven frontier, with autonomous underwater vehicles, remotely operated vehicles, robotics, and imaging technologies emerging as dominant research themes. The analysis also highlights the central role of leading countries and institutions, particularly China, the United States, and Japan, in driving scientific output and international collaborations. Importantly, the results underscore the dual focus of the field: advancing fundamental scientific knowledge while simultaneously addressing industrial interests in mineral and energy resources. While the study contributes to understanding the growth and interdisciplinarity of deep-sea exploration, it also acknowledges limitations related to database coverage and methodological scope.

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