REVIEW

Can the Ocean Save Our Future? Marine Resources as Catalysts for Educational Sustainability

Puede el océano salvar nuestro futuro? Los recursos marinos como catalizadores de la sostenibilidad educativa

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ABSTRACT

Marine ecosystems face unprecedented threats from overexploitation, pollution, and climate change, necessitating urgent integration of sustainability principles into vocational education systems. However, the intersection of marine resources and educational sustainability remains inadequately explored. This systematic scoping review investigates how marine resources can serve as catalysts for sustainability education, mapping research trends and identifying critical knowledge gaps. Data were retrieved from Scopus (1999-2024) using the keywords "Marine Resources" OR "Marine Environment" OR "Marine Ecosystem" AND "Sustainability" AND "Education," yielding 124 492 initial records. Following PRISMA guidelines and exclusion of unrelated disciplines, 77 publications from 53 sources were analyzed using Biblioshiny. The analysis examined publication trends, citation patterns, authorship networks, and thematic clusters through co-occurrence network analysis. Results revealed four distinct research phases with 9,2 % annual growth, involving 340 authors with 33,8 % international collaboration. Four thematic clusters emerged: (1) sustainability and marine environment integration (highest centrality), (2) local participation and natural resource management, (3) resource management and stakeholder engagement, and (4) environmental protection and human dimensions. Ocean literacy, marine education, and sustainability emerged as pivotal conceptual nodes connecting ecological science with pedagogical practice. The findings demonstrate growing global attention to marine education sustainability, yet reveal insufficient integration into vocational curricula. Vocational education systems must adopt structured sustainability frameworks equipping students with competencies to address marine challenges. Future research should focus on developing localized, industry-oriented curricula that strengthen vocational education as a transformative driver of long-term marine resource sustainability and conservation.

Keywords: Biblioshiny; Educational Sustainability; Marine Resources; Scoping Review; Vocational Education.

RESUMEN

Los ecosistemas marinos se enfrentan a amenazas sin precedentes por la sobreexplotación, la contaminación y el cambio climático, lo que requiere una integración urgente de los principios de sostenibilidad en los sistemas de educación profesional. Sin embargo, la intersección de los recursos marinos y la sostenibilidad educativa sigue sin explorarse adecuadamente. Esta revisión sistemática investiga cómo los recursos marinos pueden servir como catalizadores para la educación sobre sostenibilidad, mapeando tendencias de investigación e identificando brechas críticas de conocimiento. Los datos se recuperaron de Scopus (1999-2024) utilizando las palabras clave "Recursos marinos" O "Medio ambiente marino" O "Ecosistema marino" Y "Sostenibilidad" Y "Educación", lo que arrojó 124 492 registros iniciales. Siguiendo las directrices de

PRISMA y la exclusión de disciplinas no relacionadas, se analizaron 77 publicaciones de 53 fuentes utilizando Biblioshiny. El análisis examinó las tendencias de publicación, los patrones de citas, las redes de autoría y los grupos temáticos a través del análisis de redes de co-ocurrencia. Los resultados revelaron cuatro fases de investigación distintas con un crecimiento anual del 9,2 %, en las que participaron 340 autores con un 33,8 % de colaboración internacional. Surgieron cuatro grupos temáticos: (1) sostenibilidad e integración del medio marino (máxima centralidad), (2) participación local y gestión de los recursos naturales, (3) gestión de los recursos y participación de las partes interesadas, y (4) protección del medio ambiente y dimensiones humanas. La alfabetización oceánica, la educación marina y la sostenibilidad surgieron como nodos conceptuales fundamentales que conectan la ciencia ecológica con la práctica pedagógica. Los hallazgos demuestran una creciente atención mundial a la sostenibilidad de la educación marina, pero revelan una integración insuficiente en los planes de estudio vocacionales. Los sistemas de educación vocacional deben adoptar marcos estructurados de sostenibilidad que equipen a los estudiantes con competencias para abordar los desafíos marinos. La investigación futura debe centrarse en el desarrollo de planes de estudio localizados y orientados a la industria que fortalezcan la educación vocacional como un motor transformador de la sostenibilidad y conservación de los recursos marinos a largo plazo.

Palabras clave: Bibliobrillante; Sostenibilidad Educativa; Recursos Marinos; Revisión de Alcance; Educación Vocacional.

INTRODUCTION

The ocean serves as an essential natural resource for human life sustainability, providing ecological, economic, and social benefits.[1] Healthy marine ecosystems support biodiversity while supplying food, energy, and ecosystem services crucial for global community well-being.[2] However, marine ecosystems face vulnerable conditions due to increased threats from pollution, overexploitation, and climate change.[3,4] Addressing these threats requires an approach that extends beyond ecological measures to include education as a mechanism to develop community awareness and skills.[5]

Sustainability in education has an important role in shaping a generation that has a deep understanding of the importance of protecting marine resources and has the skills that can be implemented to face this global challenge.[6,7] Education that focuses on ocean sustainability needs to be structured systematically, with an approach that involves relevant curricula, practical activities, and collaboration with the industry sector oriented towards the blue curriculum.[8,9,10,11,12] The close relationship between sustainability education and learning media innovation lies in the role of both in creating a generation that is aware of global issues, able to think critically, and uses technology to convey the concept of sustainability effectively and relevant.[13,14,15] Through this approach, it is hoped that they will be able to understand the important value of marine resources as well as acquire practical knowledge and skills in managing these resources responsibly.[16]

Vocational education serves not only to enhance graduate job readiness but also to equip them with knowledge and skills that position them as key actors in marine ecosystem preservation efforts.[17] Vocational curricula based on marine resource sustainability provide students with understanding of climate change impacts, marine pollution, and fisheries overexploitation, enabling them to become agents of change toward more sustainable industries.[18]

The integration of marine resources with sustainability principles in education has evolved substantially over recent decades. Early marine education efforts focused primarily on biological and ecological knowledge transfer, with limited attention to sustainability competencies or vocational applications.[19] The formalization of ocean literacy principles in 2005 marked a pivotal shift, establishing seven essential principles that explain ocean-human interactions.[20,21,22] Subsequently, the United Nations Decade on Biodiversity (2011-2020) and the adoption of Sustainable Development Goal 14 (Life Below Water) in 2015 positioned education as a key strategy for marine conservation and sustainable resource management.[23,24]

Despite this progress, significant gaps persist in integrating marine sustainability within vocational education systems. Current vocational curricula often lack structured frameworks that connect technical skills training with marine conservation principles and sustainable development goals.[8,9,10,11,12] This deficiency is particularly critical as global demand increases for environmentally responsible marine products and services, requiring a workforce equipped with both practical skills and sustainability competencies.[17,18,25,26]

Systematic and scoping reviews have proven effective in research, particularly in vocational and marine education fields, for mapping existing evidence breadth related to sustainability education and marine resources.[27,28] Multiple literature reviews in marine environmental education have been conducted. Gough[19] highlighted critical tensions between schools and marine scientists. Pazoto et al.[20] demonstrated historical perspectives through their review of Brazilian marine education. Istiana et al.[21] emphasized that marine environmental

education should be based on local student needs, particularly in coastal communities. Bettencourt et al.[22] illustrated pedagogical shifts in marine debris education. Costa et al.[29] provided bibliometric analysis revealing ocean literacy as an underrated term in scientific literature. Paredes-Coral et al.[30] mapped global research on ocean literacy with implications for science, policy, and the blue economy.

However, no study has comprehensively mapped the relationship between marine resources and sustainability education specifically within vocational education systems to support global demand for environmentally responsible marine products and services. Current research demonstrates that effective and sustainable marine resource management is increasingly crucial for ensuring environmental sustainability, economic stability, and social well-being, especially for maritime-based nations.[24] This gap justifies a comprehensive scoping review to synthesize existing evidence and identify directions for strengthening vocational education's role in marine resource sustainability.

This scoping review aims to map existing literature on the integration of marine resources with sustainability principles in vocational education systems. By synthesizing current research, this review identifies gaps in educational approaches to marine resource sustainability and provides research and policy directions that can strengthen sustainability education integration in the marine sector. The review examines publication trends, thematic clusters, and international collaboration patterns to understand how vocational education can support more optimal marine resource conservation and management. The results are expected to form the foundation for developing educational programs that build competencies in marine sustainability to maintain marine ecosystem balance for future generations.

METHOD

Scoping review is a method of mapping out key concepts in the literature in a field, identifying research gaps, and providing a general understanding of a broad topic.[31] This scoping review adopted an established approach to mapping the scope and depth of existing evidence[32] and used the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) reporting framework.[33,34] The scoping review stages comprised four steps: identifying clear research questions to determine the study focus; identifying relevant studies on the specified topic; selecting studies to ensure exclusive inclusion of research meeting the criteria; and processing data through recording and organizing information from selected studies to analyze existing findings (figure 1).
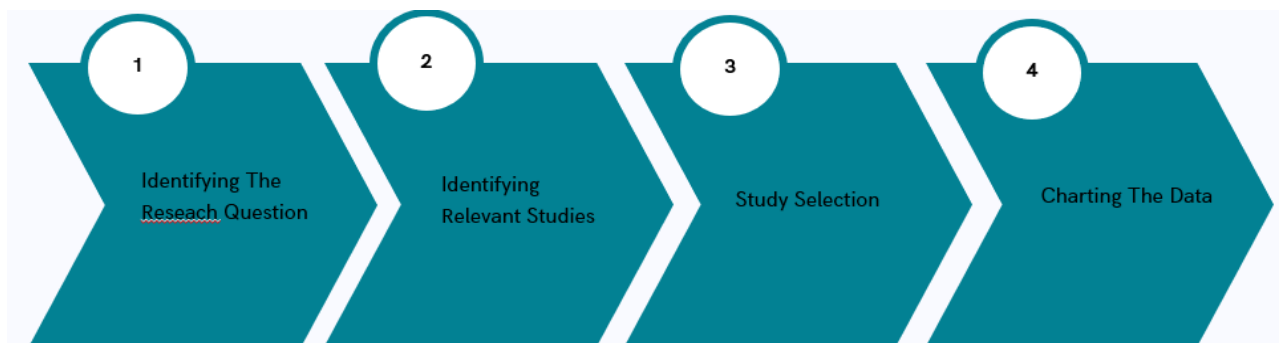

Figure 1. Research Procedure

Identifying the research question

A comprehensive and systematic approach is used to map the scope and depth of published evidence. The formulation of research questions is directed by internal and external factors to ensure the relevance and sharpness of the analysis. Review studies are excluded because a thorough search strategy has been implemented to identify relevant primary research. This research specifically focuses on sustainable marine resources and their potential integration into vocational education, with an emphasis on the issues of overexploitation, climate change, and environmental threats such as pollution.[25] Furthermore, this study examines the relationship between prevention efforts and sustainable vocational education in shaping a generation that not only understands the importance of protecting marine resources, but also has applied competencies to face these global challenges. By linking prevention-oriented learning and strengthening sustainability competencies, vocational education is positioned as a strategic instrument to foster environmental stewardship and adaptive skills in the marine sector.

Identifying relevant studies

The search strategy was developed through consultation with experts in related fields and evidence synthesis specialists, detailing marine resources and sustainable education with the keywords "Marine Resources", "Marine Environment", "Marine Ecosystem", "Education" and "Sustainability".[35,36,37,38]

Study selection

To identify relevant articles, the titles and abstracts of search results were examined against pre-defined keyword search criteria. Articles that pass the initial stage of title and abstract screening are then taken in full text for further assessment by researchers.[28] If there is a difference of opinion among researchers as to whether an article should be included, discussions are held with the other research teams to reach a final decision on whether the article is worthy of inclusion in the study.

The article identification and selection process for this scoping review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, adapted for scoping reviews.[39] As shown in figure 2, an initial search through the Scopus database using the keyword "marine resources" yielded 9519 records. The search was then extended using the keyword combination "Marine Resources" OR "Marine Environment," yielding 95 309 records. To focus the search on the educational context and interests, the search strategy was refined by adding the keywords "Marine Resources" OR "Marine Environment" OR "Marine Ecosystem" combined with "Sustainability" AND "Education," yielding 124 492 records, which were then screened.

In the initial screening stage, the titles and abstracts of the search results were evaluated based on predetermined inclusion and exclusion criteria. The criteria included studies addressing marine education, marine resources, marine ecosystems, and marine-based educational practices. Articles that met the initial criteria during the title and abstract screening stage were then retrieved in full-text form for a more in-depth eligibility assessment by the research team.[28] A total of 106 full-text articles were assessed for eligibility for inclusion in the review.
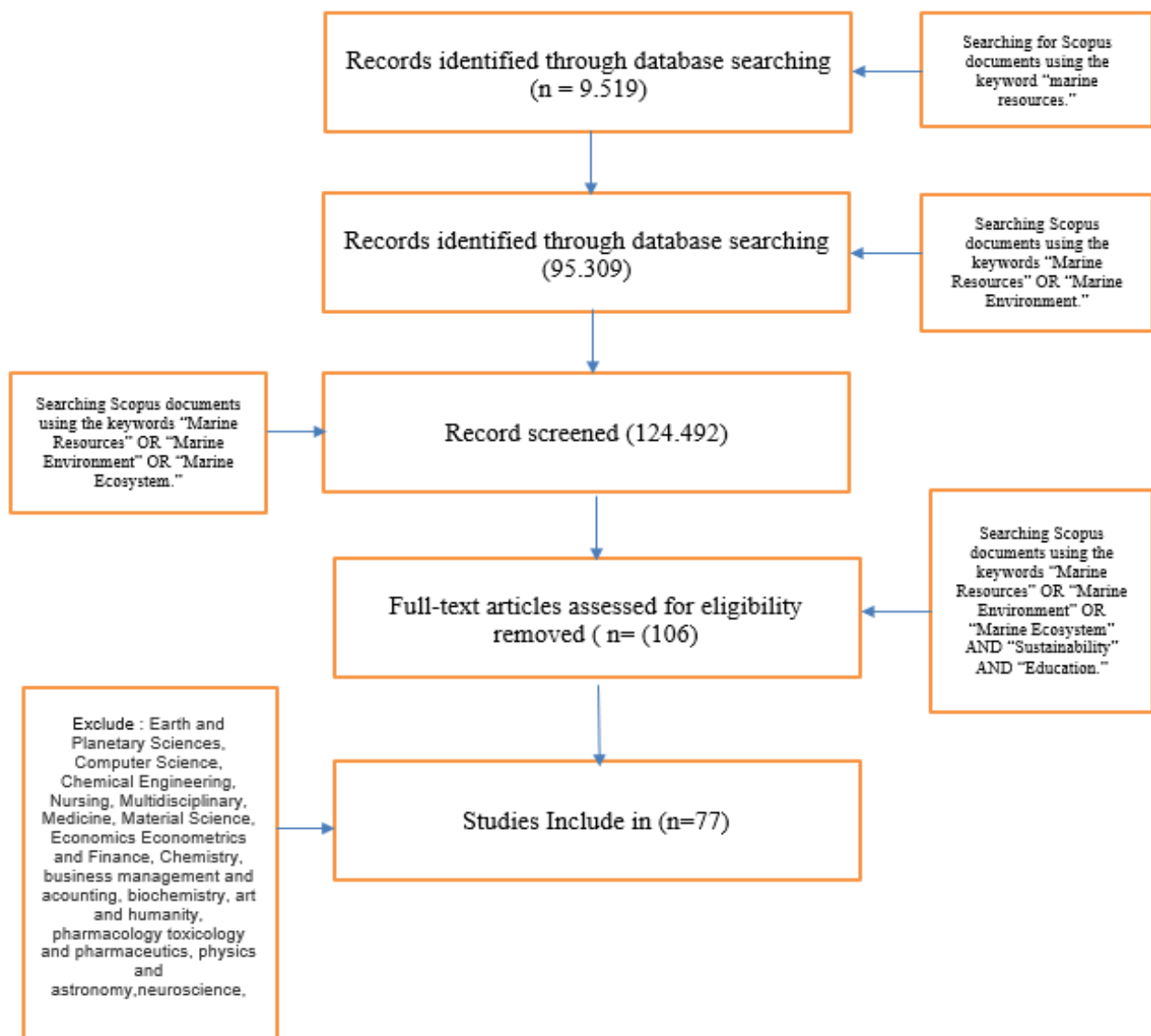
Source: https://www.prisma-statement.org/prisma-2020-flow-diagram
Figure 2. PRISMA diagram–flow of identified studies through to final inclusion adopted from

Exclusion criteria were systematically applied to ensure the relevance and focus of the study. Articles were excluded if they fell into irrelevant subject areas, such as Earth and Planetary Sciences, Computer Science, Chemical Engineering, Nursing, Multidisciplinary Medicine, Materials Science, Econometrics and Financial Economics, Chemistry, Business Management and Accounting, Biochemistry, Arts and Humanities, Pharmacology, Toxicology and Pharmacy, Physics, and Astronomy and Neuroscience. This exclusion was implemented to maintain a focus on the educational, research interests, and management dimensions of marine resources, which were at the core of this scoping review.

If there were disagreements among researchers regarding the eligibility of an article for inclusion, discussions were held involving the entire research team to establish context through a deliberation process and clarify the inclusion and exclusion criteria. This process ensured that final decisions were made collaboratively and transparently, in accordance with the principles of methodological rigor in scoping reviews.[40] After going through all stages of screening and eligibility assessment, 77 studies were finally included in the data analysis and synthesis for this scoping review.

This systematic approach, using PRISMA, ensures transparency, reproducibility, and methodological rigor in the literature selection process, ensuring that the scoping review results provide a comprehensive and credible overview of the research landscape in marine resource education for sustainability.[41]

Charting the data

The data obtained from manual search results are classified based on Article Identity, Article Keywords, Problem Formulation/Research Objectives are depicted in figure 2. Three-Field Plot Graph, Key Methods, Key Findings and Research Recommendations and Article Description. The data is used to compile reports and synthesis data. The presentation was delivered about the description in the journals that have been studied, the classification of what are the main contents that are always discussed and the presentation of the relationship with answering research questions. The Relationship between Marine Resources and Sustainability Education.

Collating, summarising and reporting the results

The results of the analysis obtained 77 documents covering the period 1999-2024, with an annual growth rate of 9,2 % and an average of 18,53 citations per document. The main content includes keywords such as sustainability, marine education, ocean literacy, and marine sustainability. These studies come from 53 sources with a total of 4290 references and involve 340 authors, of which there is an international collaboration of 33,8 %. The most common types of documents are journal articles (48 documents) followed by book chapters (10 documents) and conference papers (11 documents).

The Three-Field Plot figure shows the correlation between frequently cited references (CR), lead authors (AU), and key keywords (DE), as shown by the line flow between variables. Key references such as the work of Bennett N.J. and Costa S. Caldeira R. highlight important contributions in the literature related to marine resource sustainability and marine education. Authors such as Chang C.C., Alexander K., and Fletcher S. are major contributors to this field, with research focuses on vocational education, environmental sustainability, and marine literacy. Thus, the results of this study provide a comprehensive picture of the integration of sustainable marine resources in the education system through sustainability approaches and effective resource management.

Theoretical framework

This study is grounded in the concept of Sustainability Education Theory, which emphasizes the integration of environmental, social, and economic dimensions into educational practices to achieve long-term ecological balance.[42] This theory posits that education serves as a transformative tool to promote sustainable thinking and responsible behavior toward natural resources. Within the context of marine resources, sustainability education becomes essential in shaping students' ecological literacy, ethical awareness, and practical competencies for resource conservation. Complementing this, Ocean Literacy Theory provides a framework for understanding how individuals and communities interact with the ocean.[43] ocean literacy involves seven essential principles that explain the ocean's influence on humans and vice versa. In vocational education, integrating ocean literacy principles helps learners connect scientific understanding with socio-economic realities, thus fostering a sense of stewardship toward marine ecosystems.

From a pedagogical standpoint, the study draws upon Experiential Learning Theory,[44] which highlights learning through experience to develop skills and attitudes toward sustainability. Vocational students engaged in marine-based programs benefit from practical, context-based experiences that transform abstract sustainability concepts into actionable knowledge. This experiential approach aligns with the blue curriculum framework, which links technical skills training with marine conservation and sustainable development goals.[11] Additionally, the study is informed by Social-Ecological Systems Theory,[45] which explains how human and ecological systems are interdependent and co-evolve. In this context, vocational education functions as a

mediating institution that connects local industry, community, and environmental stewardship. The theory underscores the importance of adaptive governance and collaborative learning in achieving sustainable marine management. Integrating these theoretical perspectives provides a holistic framework for analyzing the role of vocational education in supporting marine resource sustainability. It emphasizes that educational sustainability is not only about knowledge transfer but also about developing adaptive capacities, systems thinking, and collaborative competencies that empower future professionals to maintain the resilience of marine ecosystems.

RESULTS

Table 1 shows a breakdown of data identification by searching Elsevier's Scopus database for the years 1999–2024 using related keywords. Scopus was selected as the primary database for this scoping review based on several strategic considerations. As one of the largest citation databases with over 27 000 peer-reviewed journals, Scopus offers essential multidisciplinary coverage for the inherently interdisciplinary topic of sustainable marine education.[46,47] Scopus's rigorous content curation process through its Content Selection & Advisory Board ensures the quality and credibility of the indexed literature.[42] Furthermore, advanced search features with Boolean operators and comprehensive filters facilitate a systematic and replicable search strategy, a crucial aspect of a rigorous scoping review methodology.[48] Scopus also provides bibliometric analytical tools that support the mapping of research trends and the identification of knowledge gaps, in line with the main objective of a scoping review to map the extent, range, and nature of the existing literature in a particular field.

The search in this relevant journal can be pulled forward or backward to see the data needed for the data because the reference list of the papers included in the final synthesis is searched manually. There are 124 492 articles then the Search Strategy presented is selected according to the context of the research theme, eliminating the context of unrelated journals, including Earth and Planetary Sciences, Computer Science, Chemical Engineering, Nursing, Multidisciplinary, Medicine, Material Science, Economics Econometrics and Finance, Chemistry, business management and accounting, biochemistry, art and humanity, pharmacology, toxicology and pharmaceutics, physics and astronomy, neuroscience, such as the inconsistency of the context of the theme, or other metadata elements in various electronic databases. From the articles that have been excluded, 77 relevant articles appear.

Table 1. Data Main Information by biblioshiny analysis	
Description	**Results**
MAIN INFORMATION ABOUT DATA	
Timespan	1999:2024
Sources (Journals, Books, etc)	53
Documents	77
Annual Growth Rate %	9,19
Document Average Age	6,7
Average citations per doc	18,53
References	4290
DOCUMENT CONTENTS	
Keywords Plus (ID)	657
Author's Keywords (DE)	316
AUTHORS	
Authors	340
Athors of single-authored docs	5
AUTHORS COLLABORATION	
Single-authored docs	5
Co-Authors per Doc	4,52
International co-authorships %	33,77
DOCUMENT TYPES	
article	48
book chapter	10
conference paper	11
erratum	1
note	1
review	6

The data retrieval process is illustrated in figure 2, a PRISMA diagram. After reviewing the results, articles irrelevant to the research were removed based on inappropriate thematic categories, such as Earth and Planetary Sciences, Computer Science, Chemical Engineering, Nursing, Multidisciplinary Studies, Medicine, Materials Science, Economics, Econometrics and Finance, Chemistry, Business Management and Accounting, Biochemistry, Arts and Humanities, Pharmacology, Toxicology and Pharmacy, Physics and Astronomy, and Neuroscience. Further filtering of the themes focused solely on the relationship between marine resources and sustainability education. The obtained data were then further analyzed to support research on the integration of marine resources and sustainability education.

The obtained data covered the period from 1999 to 2024, with a total of 53 sources consisting of journals, books, and other sources. The number of documents analyzed was 77, reflecting diverse contributions from various publications. The average annual growth rate reached 9,19 %, indicating a steady increase in research production. The average age of documents was 6,7 years, with an average of 18,53 citations per document. In total, 4290 references support these documents, reflecting the depth of research conducted during this period.

The content of these documents includes 657 keywords from "Keyword Plus (ID)" and 316 keywords from "Author Keyword (DE)" indicating a broad and diverse range of research topics. In terms of authors, there were a total of 340 contributing authors, with only 5 documents written by a single author. Author collaboration is significant, with an average of 4,52 authors per document, and an international collaboration rate of 33,77 %. This indicates active involvement in cross-border research collaboration. The types of documents analyzed comprised various categories, including 48 articles, 10 book chapters, 11 conference papers, 1 errata, 1 note, and 6 reviews. This distribution indicates a predominance of scholarly articles as the primary publication form, followed by contributions to conference papers and book chapters. This variety of publication types provides an overview of the diversity of research approaches and flexibility in the dissemination of research results.

Figure 3 is a Three-Field Plot that describes the relationship between three categories of variables, namely CR (Cited References), AU (Authors), and DE (Keywords). On the left side (CR), there is a list of frequently cited references, such as the work of Bennett N.J. and Costa S. Caldeira R., which show the importance of the research's contribution to the literature. In the middle (AU), the names of the main authors who contributed to the related research are listed, such as Chang C.C., Murunga M., Alexander K., and others. The line flow from the reference to the author indicates who is using a particular reference. On the right side (DE), you can see a list of the main keywords related to the research, such as sustainability, marine education, ocean literacy, marine sustainability, and citizenship. The line flow patterns between the three categories show the connectivity and distribution of research focus related to marine education, sustainability, and marine resource governance. This image provides a clear visualization of the linkages between frequently cited references, the authors involved, and the main topics in related research.
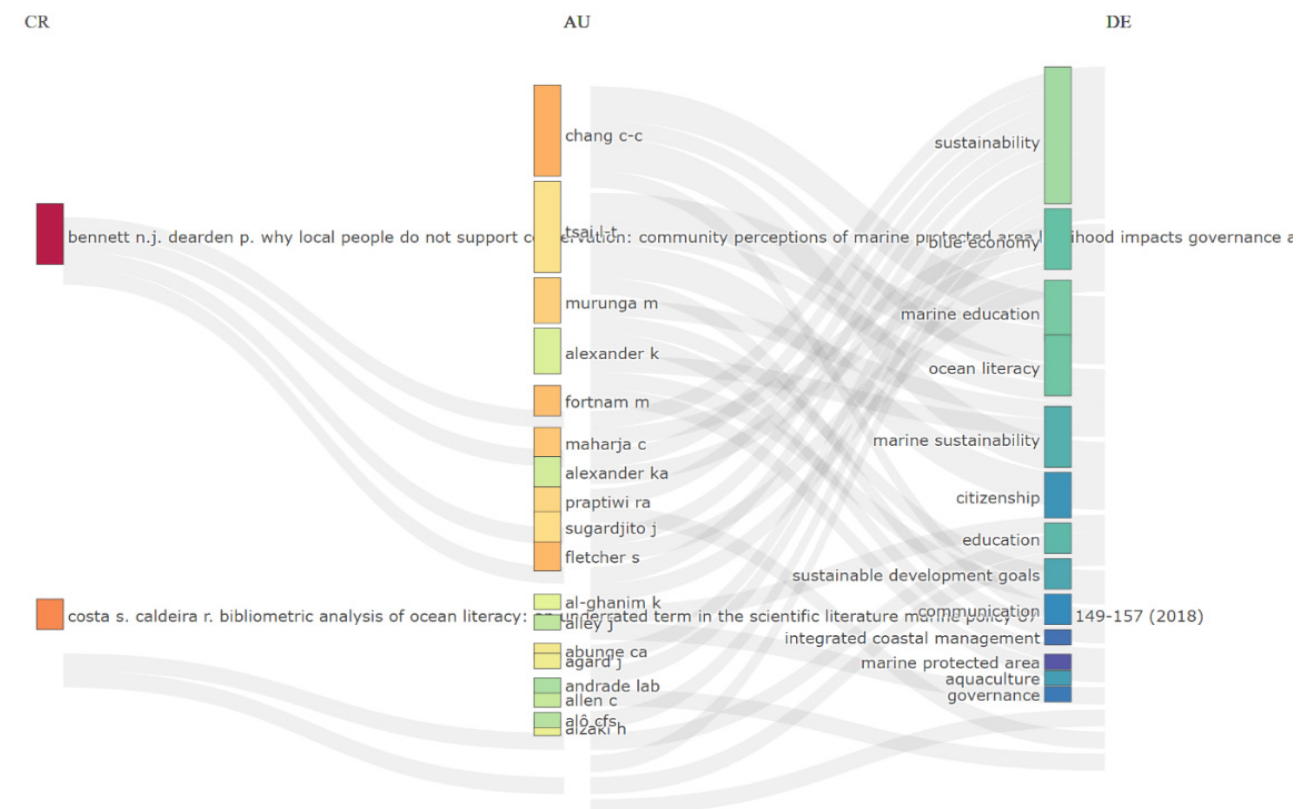

Figure 3. Three-Field Plot by biblioshiny analysis

Table 2 shows the co-occurrence network cluster 1. The analysis of the co-occurrence network shows that the topics of sustainability and marine environment stand out as the main linkages in the knowledge network related to marine and sustainable environmental management, with betweenness values of 372,57 and 273,521, respectively, as well as the highest PageRank, which is 0,113 and 0,11, indicating a significant influence and central role in scientific and policy discussions. The proximity of sustainability to other topics, as seen from the highest closeness value (0,02), reflects its high accessibility in the network. Topics such as sustainable development and education also played an important role with significant betweenness scores, 48 765 and 34 222, respectively, highlighting the role of education in supporting the sustainability agenda. Meanwhile, topics such as climate change, coastal zone management, and marine ecosystem remain relevant despite having lower metric values, demonstrating the importance of multidisciplinary approaches and adaptive policies in coastal zone and marine ecosystem management. However, topics such as fishery management, biodiversity, and anthropogenic effect show lower integration in the network, signaling the need for more attention in research and policy to strengthen their contributions to sustainable environmental management.

The co-occurrence results in Cluster 1 indicate that sustainability and the marine environment serve as the primary axis bridging biophysical issues (ecosystems, pollution, biodiversity) with socio-policy issues (education, public perception, governance, and willingness to pay/WTP). This is evident in the prominent betweenness and PageRank values of these two nodes, indicating their role as knowledge hubs that bind other terms within the network. The interconnectedness of climate change, marine ecosystems, and biodiversity underscores the chain of pressures: ocean warming, acidification, and deoxygenation drive changes in ecosystem structure and services, thus demanding more adaptive and cross-sectoral policy responses. Furthermore, the emergence of marine pollution reinforces the need for upstream to downstream resource management, particularly plastic pollution originating from land-based activities, which, according to global studies, requires integrated interventions, ranging from source reduction and product design to improved waste management systems.

The policy dimension within the network is reflected in the interconnectedness of coastal zone management, governance approaches, environmental policy, and decision-making. Classic Integrated Coastal Zone Management (ICZM) literature emphasizes the need for coastal zone management that integrates ecology, spatial planning, economics, and stakeholder participation within an iterative framework.[49]

Tabel 2. Co-occurrence Network Cluster 1 by biblioshiny analysis				
Node	Cluster	Betweenness	Closeness	PageRank
marine environment	1	273,521	0,019	0,11
sustainability	1	372,57	0,02	0,113
sustainable development	1	48,765	0,015	0,058
education	1	34,222	0,014	0,045
climate change	1	4,106	0,013	0,027
coastal zone management	1	2,35	0,013	0,025
marine ecosystem	1	6,757	0,012	0,023
marine pollution	1	1,206	0,012	0,014
perception	1	1,198	0,012	0,018
cluster analysis	1	0	0,011	0,009
coastal zone	1	0,045	0,011	0,009
decision making	1	0,086	0,011	0,009
environmental policy	1	2,005	0,013	0,019
fishery management	1	0	0,011	0,007
governance approach	1	0,345	0,012	0,013
tourism	1	0	0,011	0,008
adaptive management	1	0,151	0,011	0,008
biodiversity	1	0	0,011	0,007
environmental education	1	0,138	0,011	0,01
Indonesia	1	0	0,011	0,005
interdisciplinary approach	1	0,372	0,012	0,014
policy making	1	0	0,011	0,008
willingness to pay	1	0	0,011	0,008
anthropogenic effect	1	0	0,011	0,007

An adaptive management approach complements this through an evidence-based planning-action-evaluation cycle to address ecological and social uncertainty. The interconnectedness of interdisciplinary approaches within the cluster demonstrates that marine issues cannot be solved by a single discipline, rather, they require the integration of ecological science, policy science, economics, and education within an interdependent social-ecological system.[50]

The close association of education and environmental education with perception indicates that policy effectiveness is strongly supported by marine literacy and social support. Studies of marine education emphasize the importance of a contextual, place-based curriculum that provides opportunities for coastal community participation so that knowledge can be transformed into conservation action.[51] At the same time, the willingness to pay node demonstrates the role of economic instruments to bridge ecological evidence with conservation financing (e.g., marine destination user fees, payment for ecosystem services schemes). Valuation literature suggests that WTP increases when the public understands ecosystem benefits and believes in accountable governance.[52] Overall, the topics in cluster 1 illustrate a science-based policy pathway covering climate and pollution pressures that influence ecosystem change, ultimately impacting integrated and adaptive governance with strengthened literacy and social support, and measurable sustainability achievements.

Table 3 shows the co-occurrence network analysis result for Cluster 2. The data showed that local participation had the highest betweenness value of 11 286, indicating its crucial role as a link in this knowledge network. Local participation is a crucial element in the management and conservation of marine resources. Previous literature confirms that the success of ecosystem-based conservation is strongly influenced by the active involvement of local communities, particularly in maintaining the sustainability of marine systems.[53] Furthermore, natural resources stand out with a betweenness value of 7,653, reflecting their crucial role in discussions regarding the utilization and conservation of natural resources. As a vital resource, sustainable management of marine natural resources is key to maintaining ecological balance and supporting the livelihoods of coastal communities. The next keyword, Fisheries, with a betweenness value of 0,538, reflects the close relationship between fisheries management and other aspects of the coastal socio-ecological system. Previous research has shown that fisheries management supported by scientific data and collaboration between various actors, including local communities, has been effective in maintaining sustainable fish stocks and the well-being of coastal communities.[54] The relatively uniform closeness values for several nodes, such as fisheries, local participation, natural resources, and oceanography (0,012), indicate that these topics have relatively balanced accessibility within the network, reflecting their interconnectedness and need to be managed holistically. This is consistent with an integrated ecosystem approach that connects various aspects of science, policy, and community involvement in natural resource management.[53]

The keyword Oceanography, with the second-highest PageRank (0,016), highlights the important influence of marine studies on natural resource management. Scientific knowledge generated from marine research is essential for understanding the dynamics of marine ecosystems, including changes in marine physics, chemistry, and biology that affect the sustainability of natural resources and biodiversity. Oceanography plays a role in providing scientific data that forms the basis for effective and sustainable natural resource management policies. The analysis results show that the success of sustainable marine resource management depends on the integration of local participation with scientific knowledge (such as oceanography and fisheries).

Table 3. Co-occurrence Network Cluster 2. by biblioshiny analysis

Node	Cluster	Betweenness	Closeness	PageRank
fisheries	2	0,538	0,012	0,015
local participation	2	11,286	0,012	0,013
mozambique	2	0,154	0,009	0,008
natural resources	2	7,653	0,012	0,018
oceanography	2	1,194	0,012	0,016

Table 4 shows the co-occurrence network analysis result for Cluster 3. The data showed that resource management had the highest betweenness score of 35,936, indicating it's very important role as a liaison in this knowledge network. This highlights the need for effective resource management practices to ensure the conservation and sustainable utilization of marine resources. In addition, the topics of marine resource and stakeholder also showed significant betweenness values, amounting to 9562 and 8608, respectively, underscoring the importance of active stakeholder engagement in achieving sustainability goals. In the context of closeness, resource management has the highest score (0,014), followed by marine resource, stakeholder, and marine biology with the same value (0,013), indicating good accessibility in this network. The highest PageRank possessed by resource management (0,031) confirms the significant influence of effective management practices

in this knowledge network. Although conservation management has a lower metric value, this topic remains important in the context of marine ecosystem conservation. Overall, this analysis highlights the importance of an integrated and collaborative management approach, involving a wide range of stakeholders, to ensure sustainable and effective management of marine resources. As such, this document provides valuable insights into the dynamics and interactions of key elements in this cluster, contributing to better ocean management strategies.

Based on the co-occurrence network analysis for Cluster 3, it is clear that resource management plays a central role in marine resource sustainability. This aligns with previous studies that have highlighted the importance of resource management as a key driver of effective marine conservation.[55,56,57,58,59,60] The high PageRank score for resource management (0,031) further underscores its crucial influence in this knowledge network, which is consistent with findings from similar studies on marine resource governance.[59] Comparison of this analysis with previous studies reveals several important insights. For example, although conservation management is also relevant, its relatively low betweenness score (0,08) and PageRank (0,009) suggest that conservation management may not be as important as resource management in today's networks, possibly due to the evolving perspective on the multidimensional aspects of resource use and conservation.

Table 4. Co-occurrence Network Cluster 3 by biblioshiny analysis

Node	Cluster	Betweenness	Closeness	PageRank
marine resource	3	9,562	0,013	0,023
resource management	3	35,936	0,014	0,031
Stakeholder	3	8,608	0,013	0,02
marine biology	3	5,175	0,013	0,019
conservation management	3	0,08	0,011	0,009

Table 5 shows the co-occurrence network analysis result for Cluster 4. The data showed that environmental protection had the highest betweenness value of 16,627, indicating its central position as a link in this knowledge network. This underscores the importance of environmental protection efforts in a global context, especially in the face of increasingly complex ecological challenges. The topics human and humans also showed significant betweenness values, 5985 and 5745, respectively, emphasizing the crucial role of humans in environmental protection and management initiatives. In terms of closeness, human and environmental protection had the highest scores (0,014), indicating high accessibility in this network, allowing for quick connections with other themes. The highest PageRank was achieved by environmental protection (0,043), followed by human (0,04), confirming the significant influence of environmental protection efforts and the role of humans. Other topics such as article, conservation of natural resources, and united nations are also relevant in this discussion, albeit with lower metric values. Meanwhile, issues such as eutrophication, marine debris, and contamination have zero betweenness values, but they are still important in the context of environmental pollution and degradation. Overall, this analysis highlights the importance of a collaborative and integrated approach involving a variety of actors, including individuals and international organizations, to achieve sustainable environmental protection goals. This document provides valuable insights into the dynamics and interactions of the key elements in this cluster, as well as their contribution to more effective and sustainable environmental management strategies.

The co-occurrence network analysis for Cluster 4 highlights the crucial role of environmental protection, which emerged as the most central theme with the highest betweenness and PageRank values. This underscores the global significance of environmental protection efforts, particularly as ecological challenges become increasingly complex. The keywords "human" and "humans" demonstrate the importance of humans in driving environmental protection and management initiatives, as evidenced by their high betweenness scores. The United Nations and natural resource conservation are also key players in this conversation, albeit with lower metric values. In contrast, topics such as eutrophication, marine debris, and contamination have betweenness scores of zero, reflecting their peripheral but nonetheless important role in the broader conversation about environmental degradation. The overall findings of this analysis contribute to the broader discourse on integrated environmental management by advocating for a multi-stakeholder approach, involving individual, governmental, and international efforts. The analysis of Cluster 4 supports the growing call for a holistic and inclusive approach to addressing environmental challenges, emphasizing both local action and global cooperation for sustainable environmental protection.

We also conducted additional analysis to find out the article production data from 1999 to 2023 which can be seen in Figure 3 to find out the annual scientific article production. Based on the visualization of the number of articles from 1999 to 2024, significant fluctuations are observed throughout the period, reflecting the evolution of academic attention to marine resource education for sustainability. We divide this research development pattern into four phases, each of which exhibits distinct research development characteristics.

Node	Cluster	Betweenness	Closeness	PageRank
Table 5. Co-occurrence Network Cluster 4 by biblioshiny analysis				
human	4	5,985	0,014	0,04
Article	4	5,537	0,013	0,031
environmental protection	4	16,627	0,014	0,043
humans	4	5,745	0,013	0,036
united nations	4	0,033	0,012	0,014
conservation of natural resources	4	1,908	0,013	0,027
environmental management	4	0,025	0,011	0,01
eutrophication	4	0	0,012	0,013
marine debris	4	0	0,011	0,009
bathing beaches	4	0,118	0,012	0,012
contamination	4	0	0,012	0,013

The first phase is grouped from 1999 to 2009. This period represents an initial period with minimal productivity. The number of articles tended to be very low and stagnant, with values ranging from zero to one article per year from 1999 to 2009. This minimal productivity indicates that the topic of marine resource education for sustainability had not yet become a mainstream focus in academic discourse. This period aligns with the findings of Gough,[19] who highlighted the structural challenges in integrating marine education into formal curricula, where institutional barriers, limited teacher preparation, and the difficulty of translating complex marine science into accessible pedagogical content limited the field's development. Furthermore, during this period, the concept of ocean literacy was just beginning to develop, and the term "ocean literacy" itself was only formally formulated in 2005 through a consensus process within the scientific community in the United States. Therefore, it is understandable that academic publications remained very limited.

The second phase was from 2010 to 2015. A gradual upward trend began to emerge in 2010, marking a transition towards greater awareness of the importance of marine education. This period coincided with several important milestones in the global sustainability agenda. First, the declaration of the UN Decade on Biodiversity (2011-2020), which positioned education and public awareness as key strategies for biodiversity conservation. Second, the preparations for the ratification of the Sustainable Development Goals (SDGs) in 2015, particularly SDG 14 on Life Below Water, which explicitly recognized the role of education in achieving marine sustainability. Third, the proliferation of ocean literacy programs in various countries, particularly in North America and Europe, which began to generate documentation and academic publications.

The 2016-2020 cohort represents a period of both peak and volatility. 2016 saw the first peak with seven articles, indicating that the field was beginning to achieve some degree of consolidation. However, this period was also marked by considerable volatility, with a sharp decline in 2019 to just one article. This fluctuation likely reflects several factors. First, the interdisciplinary nature of the topic, which requires complex and time-consuming cross-disciplinary collaboration. Second, the methodological challenges of integrating diverse research approaches, from marine ecology to pedagogy. Third, the consistent limited funding for marine education research, especially compared to purely marine science research. The decline in 2019 may also be attributed to a publication lag, where research conducted during this period may not be published until subsequent years. Interestingly, a bibliometric analysis.[38] indicates that despite fluctuations in the number of publications, the 2016-2019 period marked a diversification of research methodologies and a geographic expansion of ocean literacy studies to regions beyond North America and Europe.

The 2021-2024 phase saw a post-pandemic surge in productivity. The most dramatic surge occurred in 2021 with nine articles, which then remained consistently high in subsequent years until 2024, peaking at 10 articles in 2023. This significant increase in productivity can be attributed to several converging catalysts that created tremendous momentum for sustainable marine education research.

Figure 4 show the average citation per year. The data shows the development of scientific article publications from 1999 to 2024 based on several indicators, average citations per article (MeanTCperArt), number of articles (N), average citations per year (MeanTCperYear), and number of years an article can be cited (CitableYears). In the early period (1999-2006), the number of articles and citations tended to be low, but there was a significant spike in 2007 with an average of 86,00 citations per article. The productivity trend increased after 2010, marked by an increase in the number of articles and an increase in the average citation, especially in 2016-2018, with the highest peak in 2017 (MeanTCperYear of 6,12). The highest productivity was achieved in 2021 and 2024 with 9 articles each, although in 2024 the impact of citations decreased drastically (MeanTCperArt of 0,44).

Overall, the analysis shows a significant increase in the number of publications in recent years, although the

citation effectiveness per article shows considerable variation. This phenomenon reflects the general reality in academia that the number of publications does not always directly correlate with the level of scientific influence of an article. As noted by Whitehouse[61], citation rates and impact factors are often used as indicators of journal or author prestige, but both have limitations that require careful interpretation. Differences in the scope of scientific fields within the Science Citation Index (SCI), variations in the size of scientific communities, and citation habits across fields can substantially influence citation acquisition. Therefore, an increase in the number of publications does not necessarily reflect a proportional increase in quality or scientific impact.

Furthermore, Tahamtan et al.[62] emphasized that many factors influence the number of citations of an article, including research quality, topic novelty, accessibility of publication (open access), international collaboration, and the reputation of the journal in which the article is published. They argue that most scientific papers receive few citations due to a lack of thematic relevance or limited reach to an academic audience. Conversely, articles with high quality, strong methodology, and emerging topics tend to have greater citation impact. Next, here is the data figure 5. Average Citations per Year.
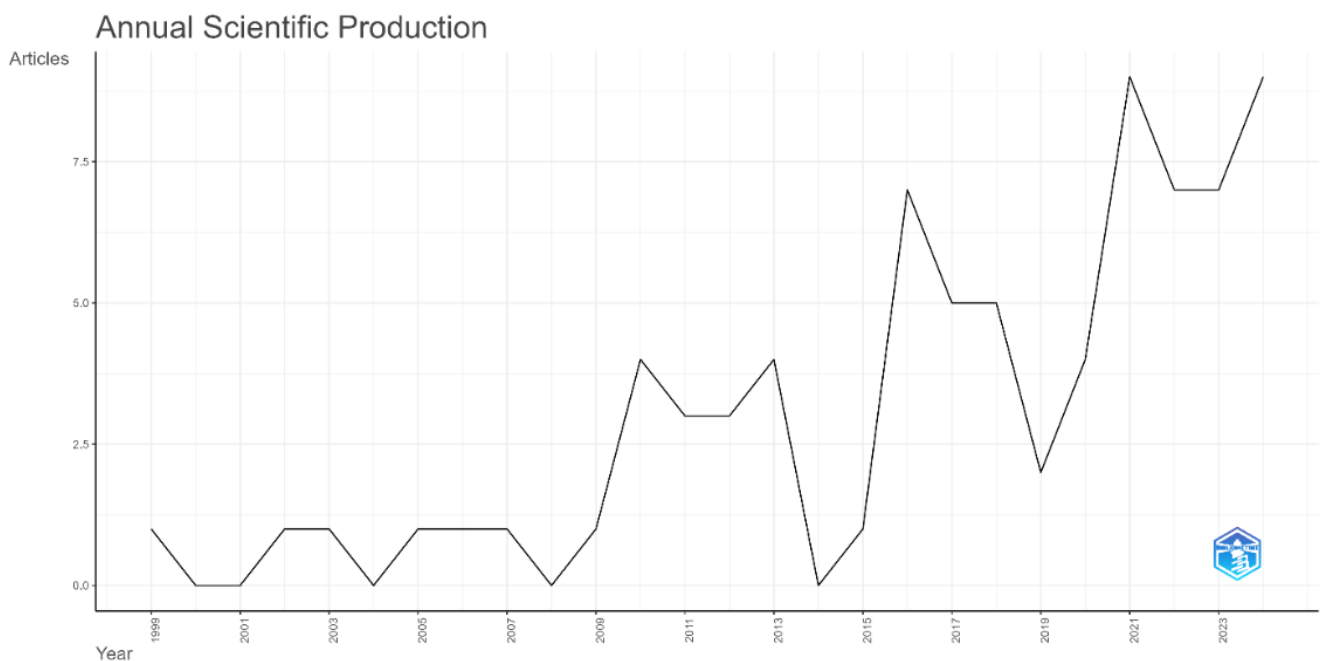

Figure 4. Annual Scientific Production Article by biblioshiny analysis
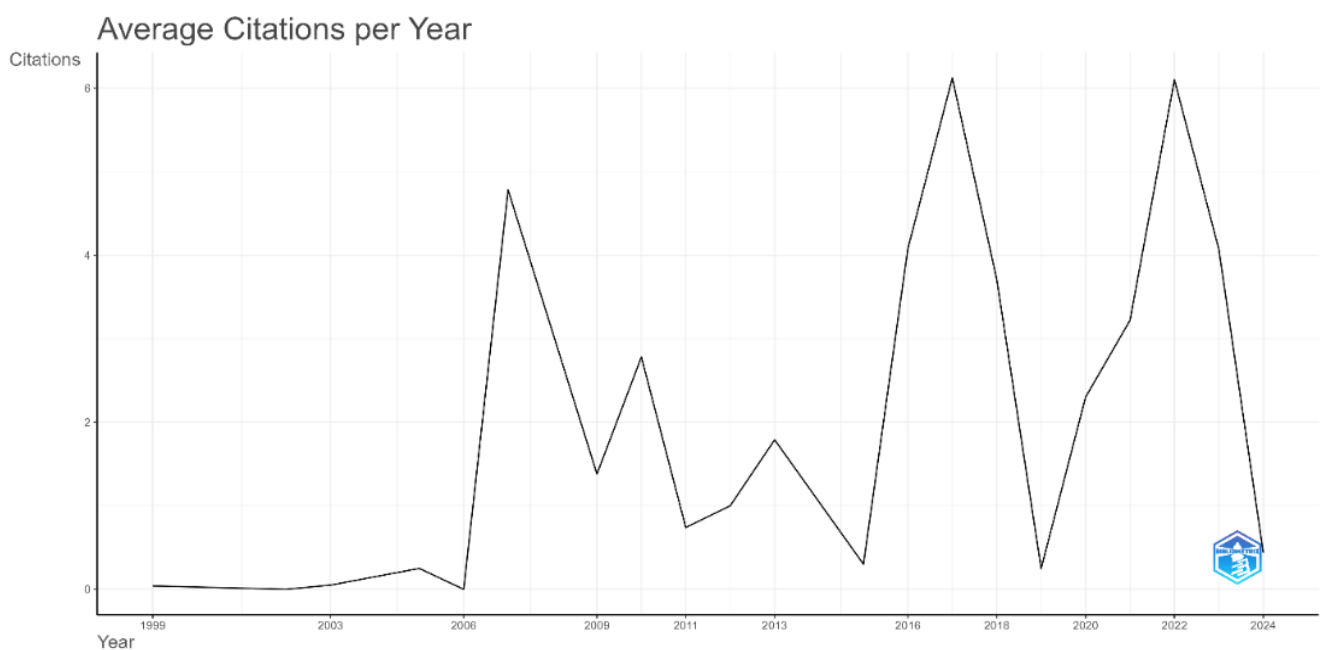

Figure 5. Average Citations per Year by biblioshiny analysis

CONCLUSIONS

This study aims to evaluate the extent to which marine resources can be integrated with sustainability principles within the vocational education system. The literature review reveals a significant increase in research trends between 1999 and 2024, indicating that the issue of marine resource sustainability and marine education is gaining increasing global attention. Conceptually, the integration of sustainability principles into vocational education is not only relevant in the context of marine resource management but also a crucial strategy in preparing young people to face the challenges of overexploitation, climate change, and marine pollution. Vocational education plays a strategic role in developing both technical competencies and ecological awareness, enabling graduates to become not only skilled workers but also agents of change towards sustainable marine management. The implications of these findings point to the need for vocational curriculum updates based on coastal and marine contexts, strengthening innovative and experience-oriented pedagogical models, and cross-sector collaboration between educational institutions, communities, and the maritime industry. Future research can be directed at developing strategic partnerships and educational policies that support the achievement of the Sustainable Development Goals (SDGs), particularly those related to quality education (SDG 4) and marine ecosystems (SDG 14). Thus, vocational education is not merely a provider of labor, but a key driver of transformation towards sustainable and responsible utilization of marine resources.

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CONFLICT OF INTEREST

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare absence of conflicting interests with the funders.

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