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Systematic Review of Chemistry Educational Strategies and Curriculum Integration in Ocean Acidification

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Abstract

This systematic literature review examines the trends and developments in ocean acidification education research from 2011 to 2025. Using the PRISMA methodology, 30 articles from the Scopus database were analyzed to identify key themes, research gaps, and future directions in teaching and learning about ocean acidification. The findings reveal a growing interest in integrating ocean acidification into science education curricula, with a significant emphasis on inquiry-based learning, technology-enhanced instruction, and interdisciplinary approaches. The United States leads research production (51 authors), followed by Spain, Sweden, and Greece. Key educational innovations include virtual reality applications, computational modelling, hands-on laboratory experiments, and collaborative learning strategies. With an average of 23.37 citations per document, this field has a substantial academic impact. However, challenges persist in terms of public awareness, teacher preparation, and curriculum integration. The review identifies the critical need for enhanced pedagogical resources, professional development programs, and assessment tools to effectively teach ocean acidification as a climate change issue. These findings provide valuable insights for educators, curriculum developers, and policymakers seeking to strengthen ocean and climate change education in formal and informal settings.

Keywords: climate change education, environmental education, ocean acidification, systematic literature review

INTRODUCTION

Ocean acidification represents one of the most pressing environmental challenges of the 21st century, often referred to as "the other CO_2 problem" in addition to climate change (Fauville et al., 2013). As atmospheric carbon $_2$ levels continue to rise due to anthropogenic activities, approximately 30% of this CO_2 is absorbed by the world's oceans, leading to decreased pH levels and significant alterations in ocean chemistry (Danielson & Tanner, 2015). This phenomenon threatens marine ecosystems, particularly organisms with calcium carbonate shells and skeletons, and has far-reaching implications for marine biodiversity, food security and coastal economies (Gorospe et al., 2013).

Despite its critical importance, ocean acidification remains largely unknown to the general public and is inadequately addressed in educational settings (Swim et al., 2017). Research indicates that even undergraduate science students have limited awareness and understanding of ocean acidification processes and their consequences (Danielson & Tanner, 2015). This knowledge gap represents a significant challenge in achieving ocean literacy and preparing future generations to address complex environmental issues.

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Education plays a fundamental role in building public understanding of ocean acidification and fostering the scientific literacy necessary for informed decision-making regarding climate change mitigation and adaptation (Fauville et al., 2021). However, teaching ocean acidification presents unique challenges owing to its invisible nature, complex chemical processes, long-term timescales, and the need to integrate knowledge across multiple scientific disciplines (Queiroz et al., 2023). Furthermore, the topic requires addressing uncertainty in scientific research while maintaining engagement and avoiding climate change fatigue among the learners.

In recent years, there have been growing efforts to develop innovative educational approaches for teaching ocean acidification, ranging from hands-on laboratory experiments to immersive virtual reality experiences (Markowitz et al., 2018; Queiroz et al., 2023). These initiatives span formal and informal education settings, target diverse age groups, and employ a variety of pedagogical strategies. However, a comprehensive synthesis of these educational efforts and their effectiveness remains limited.

Ocean acidification is fundamentally rooted in chemical processes, particularly CO_2 dissolution, carbonic acid formation, acid-base equilibrium, and carbonate chemistry. These chemical concepts align directly with the core topics in the secondary and tertiary chemistry curricula (Wilson et al., 2024). Despite this alignment, research examining how ocean acidification serves as a context for teaching chemistry, developing chemical literacy, and sustainability chemistry education remains fragmented. Chemical literacy, defined as the capacity to understand and apply chemical knowledge to real-world environmental problems, is increasingly recognized as essential in sustainability education (Wisudawati & Barke, 2024). Ocean acidification provides a compelling, real-world chemical system through which students can develop literacy while simultaneously engaging with critical global environmental issues.

Despite the growing interest in ocean acidification education, no prior systematic review has specifically analyzed how chemical concepts (such as acid-base equilibrium, carbonate chemistry, and pH) are embedded within educational strategies or how this topic is positioned within chemistry curricula and chemical literacy frameworks. This study addresses this gap by conducting a systematic literature review of ocean acidification education research published between 2011 and 2025. Specifically, this review aims to (1) map publication trends and key contributors, (2) identify dominant chemical concepts and pedagogical approaches used in teaching ocean acidification, (3) analyze how ocean acidification is integrated into chemistry curricula, and (4) assess the implications for chemical literacy and sustainability chemistry education. By analyzing 30 peer-reviewed articles, this study provides precise, focused insights into the role of chemistry education in addressing ocean acidification, offering evidence-based recommendations for educators, curriculum developers, and researchers. This study seeks answers to the following research questions:
RQ1: How has the number of publications on ocean acidification in education changed over time?
RQ2: What are the contributions of the most prolific authors and countries in ocean acidification education research?
RQ3: Which journals are most active in producing publications on ocean acidification education?
RQ4: What are the most commonly used keywords and dominant themes in ocean acidification education research?
RQ5: What educational approaches and innovations have been developed for teaching ocean acidification?
RQ6: What are the main challenges and future directions in ocean acidification education?

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METHODS

This study employed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology (Page et al., 2021) in Figure 1 to systematically identify, evaluate, and synthesize literature related to ocean acidification in educational contexts. The bibliometric analysis process followed established protocols to ensure rigor and reproducibility in the review process.

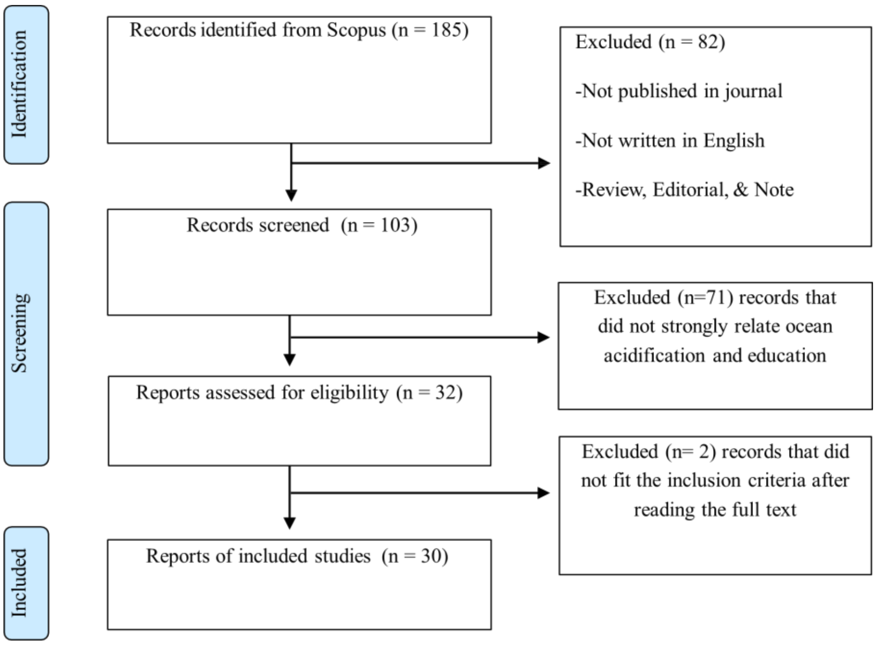

Figure 1. PRISMA flow

A comprehensive search was conducted exclusively in the Scopus database. Scopus was selected as the sole database for several reasons: (1) it is one of the largest abstract and citation databases of peer-reviewed literature, encompassing over 27,000 journals across science, technology, medicine, and social sciences; (2) it provides robust bibliometric and citation analysis tools essential for systematic and bibliometric reviews; (3) it has superior coverage of education research in natural science disciplines compared to other databases; and (4) it allows structured query syntax, enabling reproducible and precise searches (Page et al., 2021). Although Web of Science or ERIC may complement Scopus in some education reviews, the Scopus database sufficiently captures the interdisciplinary scope (chemistry, marine science, and science education) required for this study. The search strategy employed specific keywords to capture relevant publications at the intersection of ocean acidification and education topics. The following search string was used: (TITLE-ABS-KEY ("ocean acidification" OR "marine acidification" OR "sea acidification") AND TITLE-ABS-KEY (education OR teaching OR learning OR curriculum OR pedagogy))

This search strategy was designed to identify articles that explicitly addressed ocean acidification within educational contexts, ensuring that both the scientific phenomenon and its pedagogical dimensions were represented in the title, abstract, or keywords. Following the initial search, selection was conducted by applying predefined inclusion and exclusion criteria presented in Table 1. These criteria were established to ensure the relevance and quality of included studies while maintaining an

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appropriate scope for the review. The selection process followed the PRISMA flow diagram, which involved several stages:
1. Identification: Initial database search yielded potential articles
2. Screening: Titles and abstracts were reviewed for relevance
3. Eligibility: Full texts were assessed against inclusion/exclusion criteria
4. Inclusion: The final set of articles meeting all criteria was included in the analysis

This rigorous selection process resulted in 30 articles that formed the basis of this systematic review.

Table 1. Inclusion and Exclusion Criteria

Category	Inclusion Criteria	Exclusion Criteria
Publication year	2011 to 2025	Before 2011 and after 2025
Article type	Peer-reviewed Article Journal	Other type (proceeding, book, etc)
Language	English	Other languages
Subject area	Social Sciences	Other Subject area
Focus of the study	Ocean acidification within an educational context	Solely on ocean acidification without any educational component

Bibliometric analysis was conducted using two specialized software tools: VOSviewer (www.vosviewer.com) and Biblioshiny (utilizing the "bibliometrix" package in RStudio). These tools enabled a comprehensive analysis of publication patterns, keyword trends, and thematic structures within the ocean acidification education literature. The analysis included quantitative metrics (publication trends over time, citation patterns, author productivity, journal contributions, and geographic distribution), thematic analysis (keyword co-occurrence, thematic mapping, and identification of research frontiers), and content synthesis (qualitative examination of pedagogical approaches, educational innovations, and reported outcomes).

The bibliometric analysis provided insights into research trends and frontiers in ocean acidification education. Results were interpreted to identify: (1) evolution of research focus over time, (2) key contributors and their areas of expertise, (3) emerging themes and research gaps, (4) educational innovations and their effectiveness, and (5) challenges and opportunities in the field. The interpretation process involved both quantitative analysis of bibliometric data and qualitative synthesis of article content, enabling a comprehensive understanding of the ocean acidification education research landscape.

RESULTS AND DISCUSSION

General Information About Ocean Acidification Education Research

The analysis of 30 peer-reviewed articles published between 2011 and 2025, selected by the PRISMA Flow Diagram in Figure 1, reveals the scope and characteristics of research on ocean acidification in educational contexts. Table 2 presents the main bibliometric indicators for this body of literature.

The data reveal several important characteristics of ocean acidification education research. With an annual growth rate of 8.16%, the field has demonstrated steady expansion over the past 14 years.

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Table 2. General Information

Description	Results
MAIN INFORMATION	
Sources (Journals, Books, etc)	21
Annual Growth Rate %	8.16
Document Average Age	5.53
Average citations per doc	23.37
References	284
DOCUMENT CONTENTS	
Keywords Plus (ID)	99
Author's Keywords (DE)	93
AUTHORS	
Authors	92
Authors of single-authored docs	2
AUTHORS COLLABORATION	
Single-authored docs	2
Co-Authors per Doc	3.27
International co-authorships %	10

The average of 23.37 citations per document indicates substantial impact and influence within the academic community, suggesting that research in this area is being actively read, referenced, and built upon by other scholars. The collaborative nature of this research is evident in the average of 3.27 co-authors per document, reflecting the interdisciplinary nature of ocean acidification education that often requires expertise spanning marine science, chemistry, education, and pedagogy. However, the relatively low international co-authorship rate of 10% suggests opportunities for expanding global research partnerships in this field.

Publication Trends in Ocean Acidification Education

Figure 2 illustrates the annual scientific production in ocean acidification education from 2011 to 2025. The temporal pattern reveals significant fluctuations in publication activity, with notable peaks and valleys throughout the period. The early period (2011-2013) shows modest publication activity with 1-3 articles per year, suggesting that ocean acidification education was an emerging research area. A significant increase occurred in 2015-2016, with publication counts rising to 4-5 articles annually, possibly reflecting growing awareness of ocean acidification as a critical climate change issue requiring educational attention. The period from 2017 to 2021 shows variable production, with a notable peak in 2017 (6 articles) followed by lower outputs in subsequent years.

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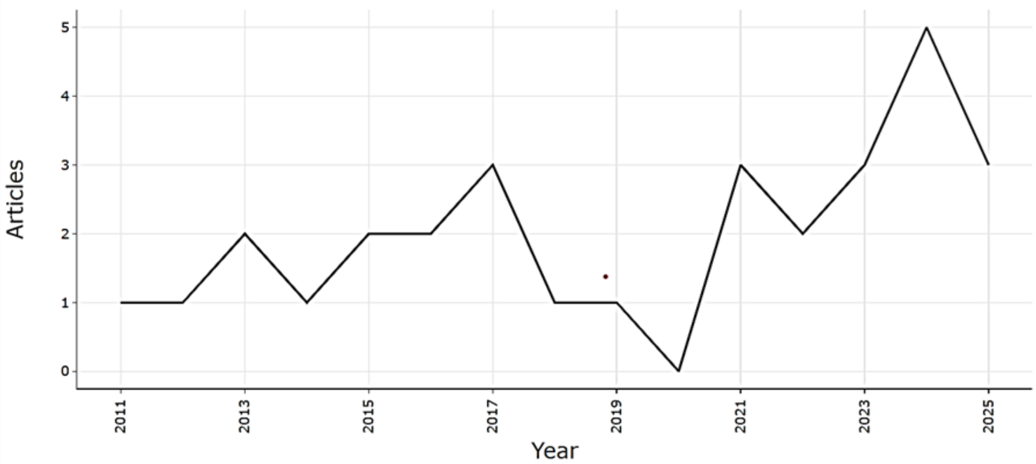

Figure 2. Annual Scientific Production

This fluctuation may reflect the complex challenges of conducting educational research on ocean acidification, including the need for specialized expertise, resources, and appropriate research contexts. A dramatic surge occurred in 2022-2023, with publication counts reaching 5-7 articles per year, the highest levels in the entire timespan. This recent increase suggests renewed interest and investment in ocean acidification education research, potentially driven by several factor. First, mounting scientific evidence about accelerating ocean acidification has increased urgency for educational responses (Hall & Cantrell, 2024). Second, technological advances, particularly in virtual reality and computational modeling, have created new possibilities for teaching this complex topic (Avcu & Yaman, 2025). Third, global initiatives such as the UN Decade of Ocean Science for Sustainable Development (2021-2030) have elevated ocean literacy as a priority. The preliminary data for 2024-2025 shows continued activity.

Contributions by Authors

The authors' contribution in Figure 3 and Figure 4 reveals the key researchers advancing ocean acidification education. Géraldine Fauville emerges as the most prolific author with multiple publications spanning several years (2013, 2017, 2021), demonstrating sustained commitment to this research area. Fauville's work has particularly focused on technology-enhanced learning, including virtual reality applications and online platforms for ocean acidification education. Other notable contributors include Bruno, who developed family-oriented ocean science education programs; Danielson, who investigated undergraduate students' conceptions and misconceptions; and Buth, who created laboratory experiments for analytical chemistry courses.

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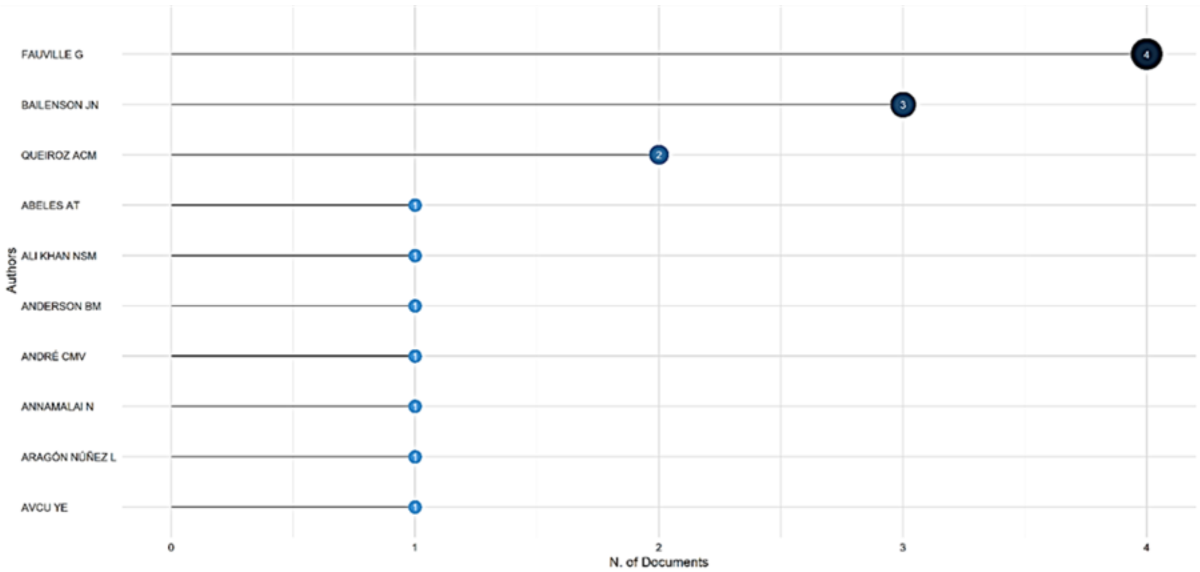

Figure 3. Most Relevant Authors

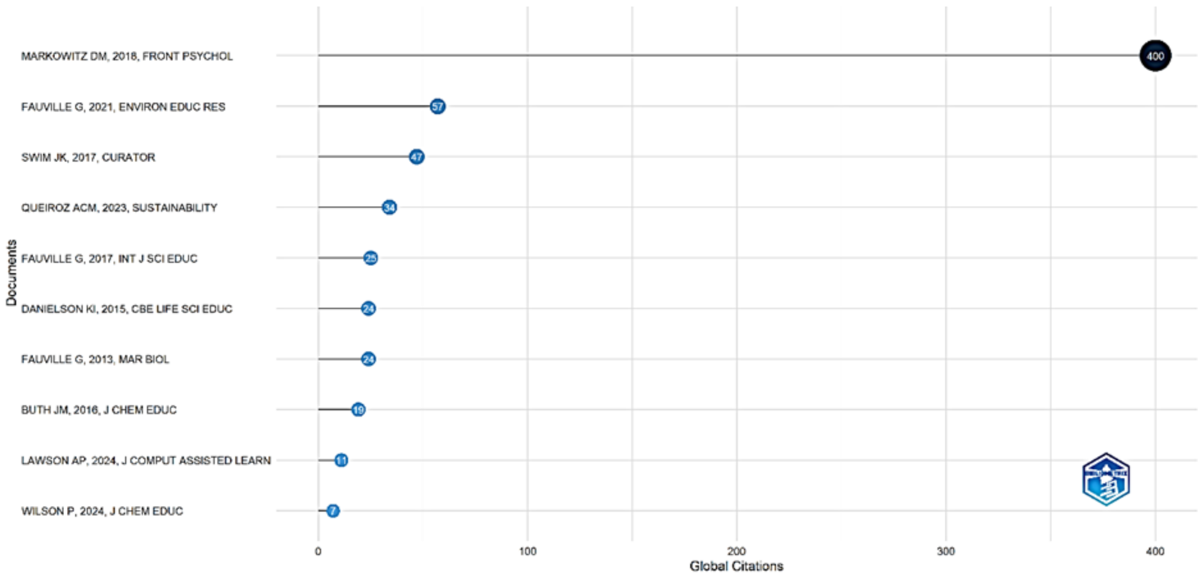

Figure 4. Most Global Cited Documents

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The diversity of these researchers' backgrounds (spanning marine science, chemistry education, and educational technology) illustrates the interdisciplinary nature of ocean acidification education research. The collaborative network analysis reveals clusters of researchers working on related themes. One cluster focuses on technology-enhanced learning and virtual reality (Fauville, Markowitz, Queiroz, Bailenson), another on laboratory-based instruction and chemistry education (Buth, Hall, Furlan), and a third on student learning and assessment (Danielson, Roche Allred, Sezen-Barrie).

Figure 4 illustrates the distribution of the most influential publications and authors based on global citation counts. The document by Markowitz, published in Frontiers in Psychology, dominates the citation landscape with 400 citations, standing far above all other works and indicating its exceptional impact within the field. Following at a considerable distance are publications such as Fauville in Environmental Education Research with 57 citations, Swim in Curator with 47 citations, and Queiroz in Sustainability with 34 citations, demonstrating a moderate yet notable level of scholarly influence. Several studies, including works by Danielson and Buth, fall within the range of 19–24 citations, indicating steady but less prominent contributions to the literature. More recent publications, such as those by Lawson and Wilson, show relatively low citation counts likely due to their recent release and limited time to accumulate citations. Overall, the figure highlights a highly uneven distribution of citation impact, with one overwhelmingly influential publication and a long tail of moderately to minimally cited studies that collectively shape the research landscape.

Contributions by Journals

Ocean acidification education research has been published across 21 different journals, reflecting the interdisciplinary nature of this field. Figure 5 presents the most active sources. The Journal of Chemical Education's prominence reflects ocean acidification's strong connection to aqueous chemistry, acid-base equilibrium, and carbonate chemistry, topics central to chemistry curricula. Articles in this journal typically present laboratory experiments and classroom activities designed to teach ocean acidification through hands-on investigation of chemical principles.

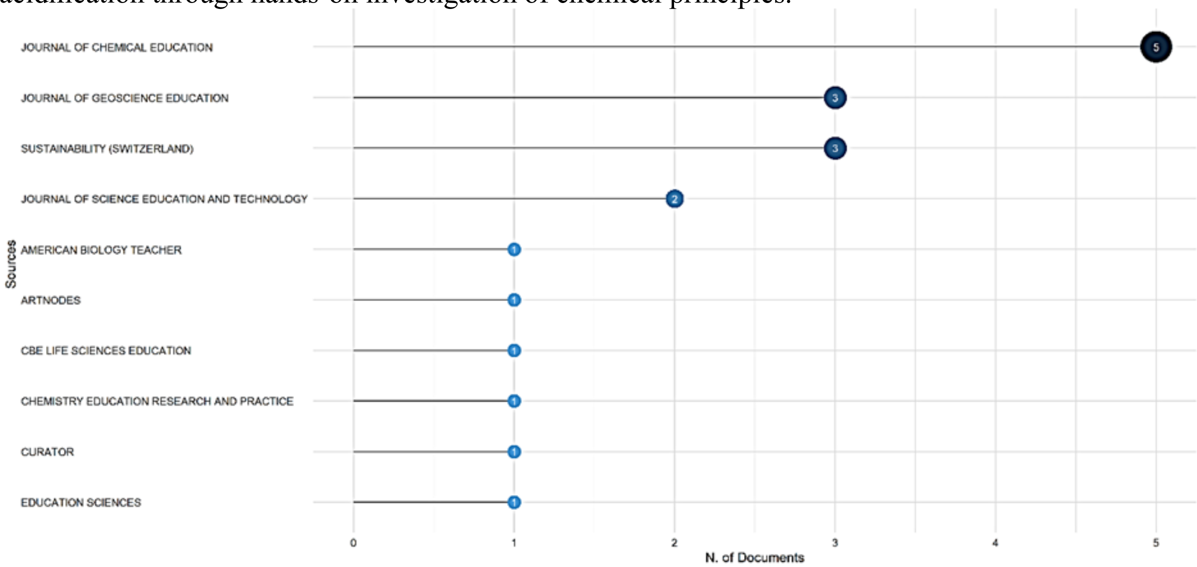

Figure 5. Most Relevant Sources

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The Journal of Geoscience Education's contributions emphasize place-based education, Earth system science perspectives, and integration with climate change education. Sustainability publishes work connecting ocean acidification education to broader environmental literacy and sustainable development goals. The diversity of publishing venues (spanning chemistry, geoscience, environmental science, and educational technology) demonstrates that ocean acidification education is not confined to a single discipline but rather serves as an integrative topic across multiple fields of science education.

Geographic Distribution

Analysis of authors' affiliations country in Table 3 and Figure 6 reveals the geographic distribution of ocean acidification education research. The United States dominates the field, reflecting several factors: (1) strong marine science research infrastructure in the U.S., (2) federal funding support for ocean science education through agencies like NOAA and NSF, (3) Presence of major research institutions with programs in ocean literacy and climate change education, and (4) Geographic proximity to diverse coastal and marine environments.

Beyond the United States, several countries have made notable contributions: (1) Spain, focus on gamified learning and environmental education approaches, (2) Sweden, emphasis on systems thinking and collaborative learning, (3) Greece, primary school education and carbon cycle understanding, and (4) Malaysia, climate change behaviors and beliefs among secondary students. Other countries with single contributions include Brazil, Germany, Indonesia, Portugal, and Turkey, indicating emerging interest in ocean acidification education across diverse geographic contexts.

Table 3. Occurrence Frequency of Authors' Affiliation Country

Author's Affiliation Country	Freq.
United States	51
Spain	5
Sweden	4
Greece	2
Malaysia	2
Indonesia	1
Brazil	1
Germany	1
Portugal	1
Turkey	1

The relatively low percentage of international co-authorships (10%) in Table 1 suggests that most research projects are conducted within national boundaries. However, this also represents an opportunity for expanding global research networks, particularly to include perspectives from small island developing states most vulnerable to ocean acidification, countries with limited resources for ocean science education, regions with diverse cultural relationships with marine environments, and southern hemisphere nations underrepresented in current research.

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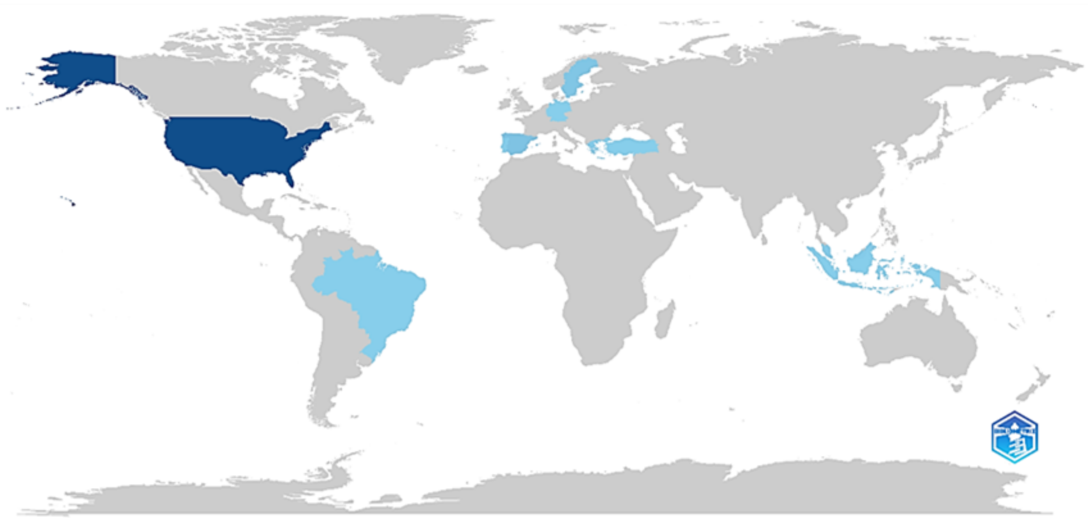

Figure 6. Country Scientific Production

Keyword Analysis and Thematic Mapping

The Three-Field Plot shown in Figure 7 illustrates the relationships between frequently occurring terms in document identification (ID), main topics found in titles and abstracts (TI_TM), and dominant descriptors or research fields (DE) within the literature on ocean acidification education. This visualization reveals how core concepts are interconnected across different levels of analysis, providing insight into the thematic structure and focus of the research field.

On the left side, the ID column highlights commonly appearing terms such as climate change, ocean acidification, carbon dioxide, student, knowledge, and disciplinary references like biology and earth science, indicating that the literature strongly situates ocean acidification within broader climate and science education contexts. The middle column, representing TI_TM, shows dominant themes in titles and abstracts, including ocean, acidification, students, chemistry, climate change, marine, virtual reality, and education, suggesting that research frequently emphasizes both the scientific mechanisms of ocean acidification and pedagogical approaches, including technology-enhanced learning. The rightmost column (DE) reflects the primary research domains and keywords, such as ocean acidification, climate change, education, environmental education, environmental chemistry, acids/bases, and hands-on learning/manipulatives, highlighting a strong orientation toward environmental and chemistry education, as well as experiential learning approaches.

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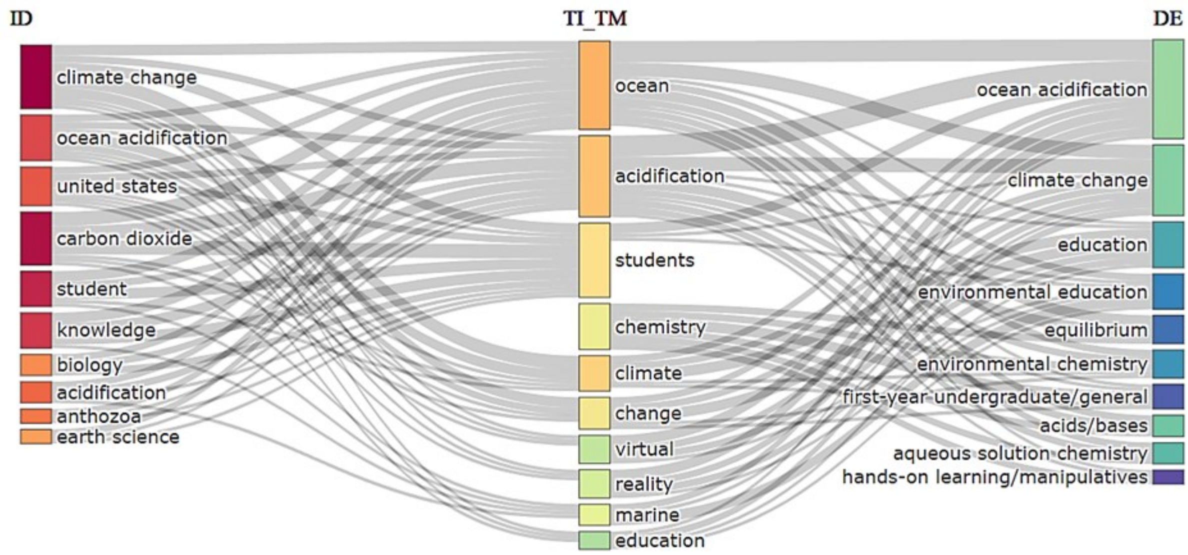

Figure 7. Three-Field Plot

The connecting lines between the columns demonstrate how foundational concepts like climate change and carbon dioxide are linked to instructional topics such as chemistry and student learning, which in turn align with dominant educational fields and pedagogical strategies. Overall, the figure shows that ocean acidification education research is highly interdisciplinary, integrating climate science, chemistry, and marine science with educational theory and practice, while also indicating emerging interest in immersive and hands-on learning approaches.

The thematic map shown in Figure 8 provides a comprehensive overview of the research landscape on ocean acidification education by positioning key themes according to their degree of development (density) and relevance (centrality). The motor themes quadrant highlights student, environmental education, and acidification as highly developed and central topics, indicating that research strongly emphasizes learners and educational approaches in explaining ocean acidification processes. Closely related to this, themes such as carbon dioxide, education, and knowledge also appear as central and relatively developed, reflecting sustained scholarly attention to conceptual understanding of the chemical drivers of ocean acidification within educational contexts.

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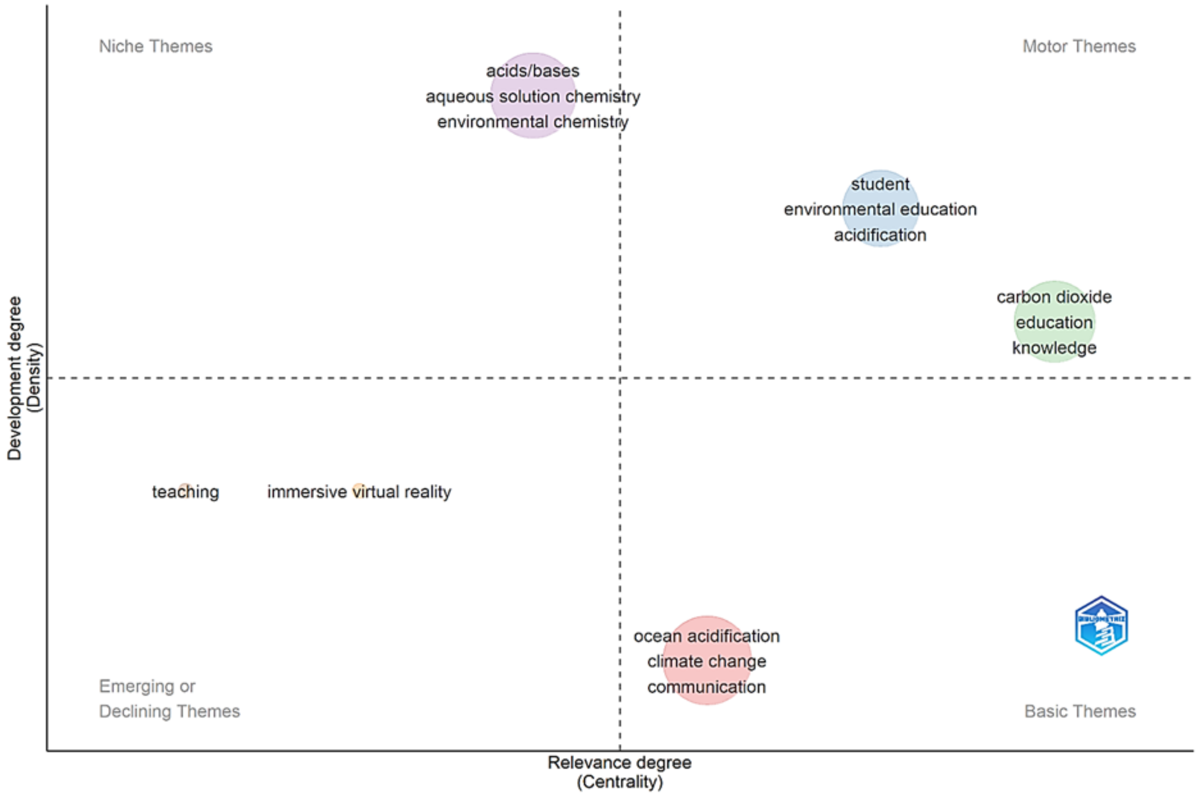

Figure 8. Thematic Map

The niche themes quadrant contains topics such as acids and bases, aqueous solution chemistry, and environmental chemistry, which are well developed but less central to the broader field, suggesting that these areas represent specialized or discipline-specific contributions that support ocean acidification education without dominating the overall research agenda. In contrast, the emerging or declining themes quadrant includes teaching and immersive virtual reality, indicating topics that are currently less developed and less central, but which may represent innovative instructional approaches that have not yet gained widespread adoption. Finally, the basic themes quadrant features ocean acidification, climate change, and communication, which are highly relevant but comparatively less developed, showing that these foundational concepts underpin much of the research but still offer significant opportunities for deeper theoretical and pedagogical development. Overall, the thematic map illustrates how ocean acidification education research is structured around core educational concerns, supported by specialized chemical concepts, while also revealing emerging instructional strategies and areas that warrant further investigation to strengthen the field.

The word cloud visualization in Figure 9 illustrates the dominant focus and thematic direction of research on ocean acidification in educational contexts. The most prominent term, ocean acidification, clearly emerges as the central concept, indicating that it is the primary subject explored across the analyzed studies. Closely associated with this core theme are climate change and environmental education, which appear with large font sizes, highlighting the strong integration of ocean acidification within broader climate-related and environmental education frameworks. The frequent presence of terms such as student, education, and knowledge suggests a substantial emphasis on learners' conceptual understanding and educational outcomes. Additionally, keywords related to disciplinary content,

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Table 4. Dominant Keyword

Category	Keyword / Concept	Number of Articles
Primary Concepts	Ocean acidification	30
	Climate change / Climate change education	18
	Environmental education	12
	Science education	10
Pedagogical Approaches	Virtual reality / Immersive virtual reality	5
	Inquiry-based learning / Hands-on learning	8
	Game-based learning / Gamification	3
	STEM education / Interdisciplinary education	4
Scientific Concepts	Carbon dioxide / CO_2	15
	pH / Carbonate chemistry	12
	Marine organisms / Coral reefs	8
	Biogeochemical cycles	4
Learning Outcomes	Scientific literacy / Ocean literacy	7
	Environmental attitudes / Behaviors	6
	Conceptual understanding / Misconceptions	5
	Systems thinking	3

including carbon dioxide, environmental chemistry, acids/bases, equilibrium, and aqueous solution chemistry, reflect the strong foundation of chemical and earth science concepts used to explain ocean acidification processes.

Pedagogical and instructional aspects are also evident through terms such as teaching, hands-on learning/manipulatives, laboratory instruction, and virtual reality, indicating growing interest in active and technology-enhanced learning approaches. References to educational levels, such as first-year undergraduate/general, second-year undergraduate, and upper-division undergraduate, further suggest that research in this area is particularly concentrated in higher education settings. Overall, the word cloud demonstrates that ocean acidification education research is characterized by a close linkage between climate science content, chemistry-based explanations, and student-centred instructional strategies aimed at strengthening understanding of complex environmental issues.

Analysis of author-supplied keywords and index terms in Table 4 reveals the dominant themes and concepts in ocean acidification education research. Based on the data presented in the table, several major thematic categories emerge that reflect the research landscape on ocean acidification in education. Under the Primary Concepts category, ocean acidification appears as the most dominant focus, featured in 30 articles, indicating its central role in the literature. This is followed by climate change and climate change education (18 articles), highlighting the strong conceptual linkage between ocean acidification and broader climate-related issues. Themes such as environmental education (12 articles) and science education (10 articles) further demonstrate that ocean acidification is commonly positioned within wider educational frameworks aimed at fostering environmental awareness and scientific understanding.

In terms of Pedagogical Approaches, the table shows a diverse range of instructional strategies used to teach ocean acidification concepts. Inquiry-based and hands-on learning are the most frequently applied approaches (8 articles), suggesting an emphasis on active student engagement and experiential learning. Emerging technologies, particularly virtual reality and immersive virtual reality, appear in 5 articles, indicating growing interest in innovative digital tools to visualize complex ocean processes. Other approaches, such as STEM or interdisciplinary education (4 articles) and game-based learning or

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Figure 9. Word Cloud Visualization

gamification (3 articles), reflect efforts to integrate ocean acidification into cross-disciplinary and motivational learning environments.

The Scientific Concepts category reveals that many studies emphasize foundational chemical and biological principles underlying ocean acidification. Carbon dioxide (CO_2) is addressed in 15 articles, underscoring its role as a key driver of ocean acidification. Closely related concepts, including pH and carbonate chemistry (12 articles), are also prominent, highlighting the importance of chemical equilibrium and buffering systems in ocean science education. Biological impacts are represented through themes such as marine organisms and coral reefs (8 articles), while biogeochemical cycles (4 articles) illustrate a systems-level perspective connecting the ocean, atmosphere, and biosphere.

Finally, the Learning Outcomes category indicates that research on ocean acidification education places strong emphasis on cognitive and affective dimensions of learning. Scientific literacy and ocean literacy emerge in 7 articles, reflecting goals related to informed understanding and decision-making about ocean-related issues. Studies focusing on environmental attitudes and behaviors (6 articles) suggest an intention to promote pro-environmental awareness and action among learners. Additionally, conceptual understanding and misconceptions (5 articles) highlight ongoing challenges in learning complex chemical and ecological processes, while systems thinking (3 articles) points to a growing, though still limited, focus on helping students understand ocean acidification as an interconnected global phenomenon.

The keyword co-occurrence analysis from Figure 10 reveals three main thematic clusters: Chemical and Scientific Foundations (Cluster 1) focuses on the chemistry of ocean acidification, including acid-base equilibrium, carbonate chemistry, and experimental investigations. Articles in this cluster typically present laboratory activities and demonstrations that help students understand the chemical mechanisms underlying ocean acidification. Technology-Enhanced Learning (Cluster 2) emphasizes innovative technologies for teaching ocean acidification, particularly virtual reality, computational modeling, and online platforms. Research in this area explores how technology can make invisible chemical processes visible and help students connect local actions to global ocean changes. Environmental Literacy and Behavior (Cluster 3) addresses broader educational goals related to climate change awareness, environmental attitudes, and pro-environmental behaviors. Articles examine how learning about ocean acidification influences students' perceptions of climate change and their willingness to take action.

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Educational Strategies and Innovations

Content analysis of the 30 articles reveals diverse educational strategies for teaching ocean acidification. Table 5 presents a classification of educational strategies, organized by strategy type, key chemical concepts addressed, and educational level.

Multiple studies describe hands-on experiments that simulate ocean acidification processes. Buth (2016) developed a multi-week analytical chemistry experiment where students pressurize seawater samples with CO_2 and measure effects on pH, carbonate ion concentration, and calcium carbonate dissolution. Furlan et al. (2023) created experiments using collagen to modulate calcium carbonate polymorph formation, connecting chemistry to marine biology. These laboratory approaches enable direct observation of chemical processes and the development of analytical skills.

Several studies examine virtual reality (VR) as a tool for ocean acidification education. Lawson & Mayer (2024) found that executive function played a larger role in learning with VR than with traditional slideshow lessons, suggesting that VR may be more cognitively demanding and its effectiveness may vary based on learner characteristics. This finding highlights the need to carefully design VR experiences to manage cognitive load while maintaining engagement. Markowitz et al. (2018) found that immersive VR field trips increased participants' knowledge and interest in learning about ocean acidification across diverse settings (museums, aquariums, arcades). Queiroz et al. (2023) demonstrated that the amount of body movement in VR experiences and message specificity both influenced learning outcomes. Avcu & Yaman (2025) showed that VR experiences enhanced gifted students' nature-relatedness and environmental attitudes. These studies suggest VR's potential to overcome barriers in ocean acidification education by making invisible chemical processes visible through visualization, creating emotional connection through immersive experiences, allowing exploration at scales and timespans impossible in physical classrooms, and engaging learners through interactive and embodied learning.

Table 5. Classification of Educational Strategies in Ocean Acidification Education

Strategy Type	Chemical Concepts Addressed	Educational Level
Hands-on laboratory experiments	Acid-base equilibrium, pH, carbonate chemistry, $CaCO_3$ dissolution	Undergraduate, secondary
Immersive Virtual Reality (VR)	CO_2-ocean interactions, visual representation of chemical change	All levels, museum
Computational modeling	CO_2 equilibrium, ocean chemistry modeling, quantitative analysis	Middle school, undergraduate
Inquiry-based learning	Scientific investigation, pH measurement, carbon cycle	All levels
Interdisciplinary STEM / gamified learning	Integrated chemistry-biology-Earth systems, environmental chemistry	Secondary, preservice teachers
Systems thinking approach	Molecular-to-global carbon reactions, biogeochemical cycles	Undergraduate, secondary

Bielik et al. (2019) investigated the use of an online computational modeling tool in a middle school ocean acidification unit. The modeling tool allowed students to manipulate variables and observe long-term trends in ocean chemistry, fostering engagement with human impacts on the environment. Hall & Cantrell (2024) developed Python coding exercises for connecting atmospheric CO_2 to ocean chemistry, introducing students to computational approaches for solving complex equilibrium problems.

Many studies emphasize inquiry-based approaches where students investigate ocean acidification through guided questioning and experimentation. Ensign et al. (2017) embedded probe-ware technology

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in an inquiry-based ocean acidification unit for preservice elementary teachers, combining technology use with investigative practices. Morais et al. (2025) engaged preservice chemistry teachers in Arduino-based problem-solving activities focused on ocean acidification, promoting interdisciplinary STEM integration.

Several studies connect ocean acidification to local contexts and communities. Bruno et al. (2011) developed family science nights focused on ocean issues relevant to Hawaiian and Pacific Island communities. Gorospe et al. (2013) created inquiry-based activities using local coral species to engage Hawaiian students in ocean acidification research. These approaches enhance relevance and cultural connections to ocean acidification.

Anderson et al. (2021) examined how educational television programs influence viewer perceptions of ocean acidification, finding improved awareness and risk perception after viewing. Peco (2021) combined sculpture and 3D technologies to create museum exhibits on ocean acidification and foraminifera, engaging public audiences in scientific outreach. These studies highlight opportunities in informal learning settings. Aragón & Brenes-Cuevas (2025) developed an escape box activity on marine plastic pollution and ocean acidification, using gamified narrative to engage students in environmental problem-solving. This approach promotes critical thinking through puzzle-solving while addressing environmental literacy.

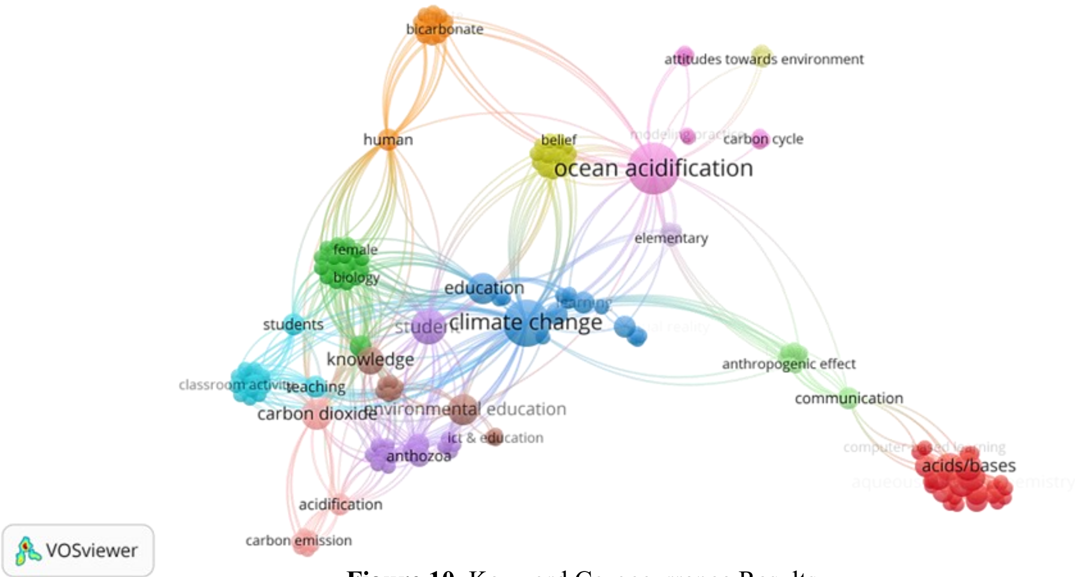

Figure 10. Keyword Co-occurrence Results

Learning Outcomes and Assessment

Research on ocean acidification education has investigated various learning outcomes. Studies reveal that many students, including undergraduate science majors, have limited initial knowledge of ocean acidification (Danielson & Tanner, 2015). Common misconceptions include confusion about the sources of ocean acidity, the relationship between climate change and ocean acidification, and the mechanisms of calcium carbonate dissolution. Educational interventions have shown positive effects on conceptual understanding. Boubonari et al. (2024) found that primary students significantly improved their knowledge of the carbon cycle and ocean acidification following an 8-hour intervention. Roche

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Allred et al., (2022) demonstrated that 93% of general chemistry students could correctly predict the relationship between CO_2 and ocean pH after completing a multidisciplinary activity.

Several studies emphasize the development of systems thinking skills through ocean acidification education. Wisudawati & Barke (2024) proposed a systems thinking approach that connects molecular-level chemical reactions to Indonesia's ocean acidification, helping students understand multiple scales and interconnections. Boubonari et al. (2024) found that their intervention improved students' systems thinking about the carbon cycle.

Research indicates that learning about ocean acidification can influence environmental attitudes and intentions. Avcu & Yaman (2025) found significant improvements in gifted students' nature-relatedness and attitudes toward the environment after VR-based instruction. Mohamed Ali Khan et al. (2021) demonstrated that knowledge, beliefs, and motivation collectively explained 65.5% of variance in climate-conserving behaviors among Malaysian secondary students. Swim et al. (2017) found that visitors to nature-based museums providing ocean acidification education were more knowledgeable, concerned, and hopeful about addressing climate change compared to non-visitors or visitors to museums without such programming.

Some studies focus on developing students' ability to communicate about ocean acidification. Sezen-barrie et al. (2023) analyzed students' explanatory models, finding that most struggled to construct cohesive explanations connecting all key ideas. Fauville (2017) examined high school students' questions to a marine scientist as indicators of ocean literacy, revealing how interaction with scientists provides entry to scientific complexity and uncertainty.

Challenges in Ocean Acidification Education

The reviewed literature identifies several persistent challenges. Ocean acidification involves abstract chemical concepts (pH, equilibrium, carbonate chemistry) that students find difficult to understand (Roche Allred et al., 2022). Integration of knowledge across chemistry, biology, and earth science presents cognitive challenges for learners. The invisible nature of chemical changes and long timescales of ocean acidification make it difficult for students to perceive urgency and connect to observable phenomena (Fauville et al., 2021). Ocean acidification remains relatively unknown compared to other climate change issues. Danielson & Tanner (2015) found low awareness even among undergraduate science students. Anderson et al. (2021) reported that student awareness of ocean acidification was "extremely low" before educational intervention. Fauville et al. (2021) identified lack of science literacy, unprepared educators, the complex nature of ocean acidification, and lack of personal connection with the ocean as major barriers to teaching this topic. Many educators lack confidence, resources, and professional development opportunities. Wilson et al. (2024) found that despite viewing climate change (including ocean acidification) as highly valued, most chemistry instructors taught it tangentially or not at all, citing time constraints and standardization as barriers.

Thematic Evolution Over Time

Analysis of themes across the publication timeline reveals the evolution of research focus. Early Period (2011-2015), initial publications emphasized basic awareness, conceptual understanding, and development of laboratory activities to demonstrate ocean acidification processes. Middle Period (2016-2020), research expanded to include technology-enhanced learning (VR), assessment of student misconceptions, and connections to climate change education more broadly. Recent Period (2021-2025), current research emphasizes interdisciplinary integration (STEM), advanced technologies (immersive VR, computational modeling), systems thinking, and environmental attitudes/behaviors. There is also growing attention to diverse contexts (gifted students, preservice teachers, international settings).

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Ocean acidification provides a powerful context for integrated STEM education, requiring knowledge from chemistry (acid-base equilibrium, solubility), biology (organismal responses, ecosystem effects), earth science (carbon cycle, climate systems), and mathematics (data analysis, modeling). Several studies successfully demonstrated interdisciplinary integration (Morais et al., 2025; Roche Allred et al., 2022) though challenges remain in helping students make connections across disciplinary boundaries. Systems thinking emerges as a critical competency for understanding ocean acidification (Boubonari et al., 2024; Wisudawati & Barke, 2024). Ocean acidification cannot be fully understood in isolation; it requires recognizing connections across multiple scales (molecular to global), timeframes (immediate to centuries), and systems (atmosphere, ocean, biosphere, human society). Educational approaches that explicitly develop systems thinking skills appear particularly effective for building comprehensive understanding. The challenge of scale is particularly important. Ocean acidification involves phenomena at multiple scales: molecular (proton transfer, carbonate speciation), organismal (shell dissolution, physiological stress), ecosystem (food web disruptions, biodiversity changes), and global (carbon cycle, climate feedbacks). Educational materials must help students navigate across these scales and understand how processes at one scale influence others.

A critical question in ocean acidification education is whether learning about this issue translates to environmental attitudes and behaviors. Several studies provide encouraging evidence that well-designed educational experiences can influence not only knowledge but also attitudes, concern, self-efficacy, and behavioral intentions (Avcu & Yaman, 2025; Mohamed Ali Khan et al., 2021; Swim et al., 2017). However, the pathway from knowledge to action is complex. Mohamed Ali Khan et al. (2021) found that while knowledge, beliefs, and motivation all positively influenced climate-conserving behaviors among Malaysian students, motivation had the strongest effect ($\beta = 0.546$), followed by beliefs ($\beta = 0.295$) and knowledge ($\beta = 0.259$). This suggests that effective ocean acidification education must address not only cognitive understanding but also emotional engagement, values, self-efficacy, and opportunities for action. The role of hope and empowerment deserves particular attention. Given the serious nature of ocean acidification impacts, education must avoid creating paralysis or despair. Swim et al. (2017) found that museum visitors exposed to ocean acidification education were more hopeful about their ability to talk about the topic and more likely to engage in actions, suggesting that educational experiences can build agency alongside awareness. Design of educational materials should carefully balance realism about challenges with emphasis on solutions and opportunities for individual and collective action.

The challenges identified by Fauville et al. (2021) in teaching ocean acidification (lack of science literacy, unprepared educators, complex nature of content, and lack of personal connection) highlight the critical importance of teacher preparation and professional development. Yet relatively few studies in this review directly addressed teacher education (Ensign et al., 2017; Morais et al., 2025). Research on preservice teachers (Ensign et al., 2017; Morais et al., 2025) suggests that hands-on experience with probeware, modeling tools, and inquiry-based activities during teacher preparation can increase confidence and intention to use these approaches in future teaching. However, the conditional nature of these intentions (dependent on positive experiences and perceived support) emphasizes the need for high-quality, well-supported learning experiences in teacher education programs. Professional development for in-service teachers represents a significant need. Swim et al. (2017) demonstrated that the NNOCCI (National Network for Ocean and Climate Change Interpretation) training program created institutional cultures supportive of climate science education at nature-based museums. Similar systematic professional development programs for K-12 teachers could support widespread integration of ocean acidification into science curricula.

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Despite growing research on ocean acidification education, assessment of learning outcomes remains underdeveloped. Most studies use pre-posttests of conceptual knowledge or surveys of attitudes, with limited attention to more complex learning outcomes such as systems thinking, argumentation quality, or scientific practices. Sezen-barrie et al. (2023) proposed a qualitative framework for analyzing students' explanatory models that considers both conceptual coherence and epistemic discourses. Their finding that most student models were "insufficiently cohesive" highlights the challenge of helping students construct integrated understanding. Development and validation of assessment tools that can capture the complexity of ocean acidification understanding (including conceptual knowledge, systems thinking, scientific practices, and environmental literacy) remains an important priority. Additionally, most studies assess immediate or short-term outcomes, with limited research on long-term retention of knowledge or sustained behavioral changes. Longitudinal studies that follow students over months or years could provide important insights into the lasting impacts of ocean acidification education.

While several studies addressed ocean acidification education in diverse settings, equity considerations remain underexplored. Questions of access to educational resources (especially technology-enhanced approaches requiring VR equipment or sophisticated modeling tools), representation of diverse communities in educational materials, and relevance of ocean acidification to students' lives and communities deserve greater attention. Bruno et al. (2011) and Gorospe et al. (2013) demonstrate how place-based approaches can make ocean acidification personally and culturally relevant to Hawaiian and Pacific Islander students. Similar efforts to connect ocean acidification to the experiences and concerns of diverse communities (including inland communities affected through seafood availability and economic impacts) could enhance engagement and relevance. Peco (2021) included blind-accessible explanatory signage in their museum exhibit, demonstrating attention to accessibility. As the field develops innovative educational approaches, explicit consideration of accessibility and universal design principles can ensure that ocean acidification education reaches diverse learners.

CONCLUSION

This systematic literature review of 30 peer-reviewed articles published between 2011 and 2025 provides comprehensive insights into the emerging field of ocean acidification education. The findings reveal a growing but still relatively small research area characterized by steady annual growth (8.16%), substantial academic impact (23.37 citations per document), and increasing innovation in pedagogical approaches. Researchers have developed and tested diverse approaches for teaching ocean acidification, including hands-on laboratory experiments, immersive virtual reality experiences, computational modeling tools, inquiry-based activities, and gamified learning. Each approach demonstrates effectiveness for particular learning goals and contexts. Educational interventions have successfully improved conceptual understanding, systems thinking, environmental attitudes, and behavioral intentions related to ocean acidification. However, effectiveness varies based on design quality, implementation context, and learner characteristics.

Significant challenges remain in teaching ocean acidification, including its conceptual complexity, invisible nature, low public awareness, inadequate teacher preparation, and barriers to curriculum integration. Time constraints and standardization pressures limit teachers' ability to address this topic comprehensively. Ocean acidification provides a powerful context for integrated STEM education and systems thinking development, though helping students make connections across disciplines and scales remains challenging. Research is heavily concentrated in the United States, with limited representation of diverse geographic, cultural, and educational contexts. Expanding international collaboration and research in vulnerable regions represents a critical need. Emerging technologies, particularly virtual

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reality and computational modeling, offer exciting possibilities for making ocean acidification tangible and engaging. However, these approaches require careful design to manage cognitive load and ensure accessibility.

Educational Implications

The findings of this review carry significant implications for chemistry and science education. First, ocean acidification should be formally integrated into chemistry curricula as a real-world context for teaching acid-base equilibrium, carbonate chemistry, and solubility, concepts already present in national and international science standards. This integration supports chemical literacy by connecting abstract chemical principles to tangible environmental consequences. Second, teacher preparation programs should explicitly include ocean acidification as a model topic for teaching sustainability chemistry, equipping preservice and in-service teachers with both content knowledge and pedagogical strategies such as inquiry-based experiments, VR, and computational modeling. Third, curriculum developers should design assessment tools that measure chemical literacy outcomes in the context of ocean acidification, moving beyond factual recall to evaluate systems thinking, argumentation, and application of chemical concepts. Finally, the underrepresentation of Global South nations in this literature signals an urgent need to develop culturally relevant, resource-appropriate chemistry education materials on ocean acidification for diverse educational systems, particularly in coastal and island developing nations most affected by this phenomenon.

Ocean acidification can be effectively taught through diverse approaches, from simple laboratory demonstrations to sophisticated VR experiences. Educators should select and adapt approaches based on learning goals, student needs, and available resources. Emphasis on connections to climate change, local contexts, and opportunities for action can enhance relevance and engagement. Ocean acidification should be integrated more comprehensively into science curricula as a lens for teaching chemistry concepts (equilibrium, solubility), biological processes (organismal responses, ecosystem dynamics), and Earth systems (carbon cycle, climate change). Materials should scaffold systems thinking and support students in making connections across disciplines and scales. Preservice and in-service teacher education programs should provide opportunities for teachers to develop their own understanding of ocean acidification and gain confidence using inquiry-based, technology-enhanced, and interdisciplinary approaches. Hands-on experience with teaching strategies during professional development can increase likelihood of implementation. Nature-based museums, aquariums, and science center play important roles in ocean acidification education. Institutional support, professional development (such as NNOCCI training), and high-quality exhibit design can create impactful learning experiences for diverse public audiences.

Future Research Directions

Based on this systematic review results, there are several priority areas for future research: (1) future studies should develop and validate instruments specifically designed to assess chemical literacy in the context of ocean acidification, capturing understanding of acid-base chemistry, carbonate systems, and their connections to sustainability; (2) empirical studies are needed to document how ocean acidification is integrated into chemistry curricula across national contexts, identifying structural and attitudinal barriers; (3) long-term follow-up studies examining whether educational interventions produce durable changes in chemical literacy, environmental attitudes, and pro-environmental behaviors would substantially strengthen the evidence base; (4) controlled comparative studies are needed to determine the relative effectiveness of different pedagogical strategies (laboratory experiments, VR, modeling) for teaching specific chemical concepts within ocean acidification; (5) research from the Global South, particularly from small island developing states, Southeast Asia, and Africa, is critically underrepresented and should receive dedicated investigation; and (6) future work should explicitly situate ocean acidification within sustainability chemistry education frameworks, examining how this topic can be used to develop green chemistry thinking and responsible citizenship among learners.

Ocean acidification represents both a critical environmental challenge and a valuable educational opportunity. As "the other CO_2 problem," it provides a concrete entry point for understanding human impacts on Earth systems and the urgency of climate action. The research reviewed here demonstrates that effective education about ocean acidification is possible and can contribute to broader goals of climate literacy and environmental citizenship. However, realizing this potential requires sustained effort from multiple stakeholders. Researchers must continue developing evidence-based practices while addressing identified gaps. Educators need high-quality resources, professional development, and institutional support to teach this complex topic effectively. Policymakers should prioritize ocean literacy in science standards and provide funding for education research and program development. Public science communicators must work to raise awareness and make ocean acidification personally relevant to diverse audiences.

As ocean acidification accelerates and its impacts become increasingly apparent, the need for widespread public understanding becomes ever more urgent. Education represents our best hope for building the scientifically literate, environmentally conscious citizenry necessary to address this and other climate challenges. This systematic review contributes to that effort by synthesizing current knowledge, identifying effective practices, and charting directions for future advancement of ocean acidification education. The "last great hope" that Schmeisser & Doss (2012) spoke of, an informed geoscience community and public able to understand and respond to human transformations of Earth systems depends on education. By continuing to innovate, research, and improve ocean acidification education, we can help prepare future generations to be effective stewards of our changing ocean planet.

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