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Review Article

STEM-Based Learning in Early Childhood Education: A Systematic Literature Review on Children's Scientific Literacy

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ABSTRACT

Purpose of the study: This study aims to systematically map the development of global research on STEM-based learning in early childhood education, with a focus on research trends, dominant themes, implementation characteristics, and their contribution to the development of children's scientific literacy.

Methodology: A Systematic Literature Review (SLR) was conducted by integrating bibliometric analysis and thematic synthesis of 158 scientific articles obtained from research databases. The analysis involved mapping publication developments, keyword analysis, research networks, and identifying key themes related to STEM learning and early childhood science literacy.

Main Findings: The findings reveal a significant growth in publications on STEM-based learning in early childhood education, reflecting increasing global attention to early scientific literacy development. Bibliometric analysis identifies scientific literacy, STEM education, science education, curriculum, and engineering education as dominant research themes. Thematic synthesis shows that STEM implementation is commonly conducted through play-based learning, exploration, simple experiments, investigation, and problem-solving activities, supporting children's scientific literacy and 21st-century competencies.

Novelty/Originality of this study: This review makes a novel contribution by integrating bibliometric analysis and thematic synthesis to map global research on STEM learning in early childhood education. It expands on previous understanding by identifying research trends, characteristics of STEM implementation, and developing a conceptual framework linking STEM learning ecosystems, authentic experiences, and children's scientific literacy development.

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1. INTRODUCTION

The development of the 21st century has brought various global challenges, including climate change, health crises, digital transformation, and the spread of missinformation, which require individuals not only to understand scientific concepts but also to critically evaluate information, solve problems, and make evidence-based decisions [1], [2]. In this context, scientific literacy has become an essential competency that enables individuals to understand scientific phenomena, evaluate scientific information, apply evidence appropriately, and use scientific knowledge in everyday contexts [3], [4]. Therefore, strengthening scientific literacy from an early stage of education is increasingly recognized as an important foundation for preparing individuals to face complex societal challenges.

STEM-based learning has emerged as an educational approach that supports the development of these competencies by integrating science, technology, engineering, and mathematics through interdisciplinary and contextual learning experiences [5], [6]. Unlike traditional approaches that often separate disciplinary knowledge, STEM emphasizes investigation, problem identification, solution design, modeling, testing, and reflection through authentic problem-solving activities [7]-[10]. This approach reflects a shift from learning about science toward learning through science, where learners actively engage in scientific and engineering practices, including asking questions, conducting investigations, analyzing evidence, constructing explanations, and designing solutions [11]-[14]. Consequently, STEM learning has a strong conceptual relationship with scientific literacy because both emphasize inquiry, evidence-based reasoning, and the application of scientific knowledge in real-life situations [15]-[17].

In early childhood education, the development of scientific literacy is particularly important because children's scientific thinking begins to develop through curiosity, exploration, observation, questioning, and interaction with their surrounding environment [20]-[22]. At this educational level, STEM should not be interpreted as formal instruction of complex science, technology, engineering, and mathematics concepts, but rather as developmentally appropriate learning experiences involving play, exploration, investigation, and problem solving [23]-[25]. Previous studies have demonstrated that STEM activities, including engineering design, maker activities, project-based inquiry, exploration of natural phenomena, and constructive play, provide opportunities for children to develop observation skills, prediction abilities, communication, creativity, and early scientific reasoning [14], [26]-[34].

Empirical studies further indicate that STEM experiences in early childhood contribute to the development of scientific thinking, creativity, problem-solving abilities, communication skills, early mathematical understanding, and engineering habits of mind [24], [35]-[43]. Through activities such as constructing structures, exploring environmental phenomena, conducting simple experiments, and designing solutions to everyday problems, children can engage in scientific practices by observing, predicting, testing ideas, improving solutions, and communicating their findings [26], [27], [44]-[46]. However, effective STEM implementation in early childhood education depends on several supporting factors, including teachers' pedagogical competence, the availability of learning resources, the quality of the learning environment, and family support in providing meaningful exploratory experiences [47]-[50].

Although studies on STEM in early childhood education have increased significantly, several research gaps remain. Previous studies have mainly examined STEM outcomes related to creativity, problem-solving skills, mathematical development, general science attitudes, or 21st-century competencies, while comprehensive evidence regarding how STEM-based learning contributes specifically to different dimensions of children's scientific literacy remains limited [51]–[53]. Furthermore, existing studies demonstrate considerable variation in educational contexts, STEM implementation models, research designs, and learning objectives, making it difficult to obtain a comprehensive understanding of global research trends, dominant themes, implementation characteristics, and future research directions [5], [54]. In addition, challenges related to technology integration, contextual differences among educational settings, and the preparation of educators continue to influence the effectiveness of STEM implementation in early childhood education [55], [56]. Therefore, a systematic review is needed to synthesize existing evidence and provide a comprehensive understanding of the relationship between STEM-based learning and children's scientific literacy development.

Based on these research gaps, this study aims to systematically review global research on STEM-based learning in early childhood education and its contribution to children's scientific literacy development. Specifically, this study addresses the following research questions: (1) How has research on STEM-based learning and children's scientific literacy developed globally? (2) What are the dominant themes and characteristics of STEM implementation in early childhood education? (3) How does STEM-based learning contribute to the development of children's scientific literacy? Through bibliometric analysis and thematic synthesis, this study provides theoretical insights into the development of STEM and scientific literacy research while offering practical implications for teachers, curriculum developers, and researchers in designing meaningful STEM learning experiences that are appropriate for young children's developmental characteristics.

2. RESEARCH METHOD

This study used a Systematic Literature Review (SLR) approach to identify, analyze, and synthesize research findings on the implementation of STEM-based learning and its relationship to scientific literacy development. The SLR approach was chosen because it allows for a systematic, transparent, and replicable literature review process through the search, selection, evaluation, and synthesis stages of various relevant studies. This review process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses

(PRISMA) guidelines, which encompass four main stages: identification, screening, eligibility, and included studies. The PRISMA approach was used to ensure objective article selection and minimize potential bias in the literature selection process.

Data collection was conducted through the Scopus database, the primary source of scientific publications. Articles were searched using a combination of keywords related to STEM and scientific literacy, including article titles, abstracts, and keywords. The search strategy used the following keywords: ("STEM" OR "STEM education" OR "Science Technology Engineering Mathematics") AND ("scientific literacy" OR "science literacy"). Based on the initial search results, 621 articles were retrieved. The selection process was then carried out in stages based on established inclusion and exclusion criteria, including document type, publication language, and article access availability.

In the document type screening stage, articles not categorized as scientific journal articles were excluded from the selection process. These included book chapters (43 articles), conference papers (37 articles), review articles (22 articles), and books (16 articles). After document screening, 282 articles met the criteria for the next selection stage. Subsequent screening was conducted based on publication language, excluding articles not in English: articles in Spanish (6 articles), Chinese (4 articles), Russian (2 articles), Portuguese (1 article), Lithuanian (1 article), and Croatian (1 article). This resulted in 271 articles. The final selection stage was based on publication access availability, excluding articles classified as Gold (111 articles), Green (89 articles), Hybrid Gold (23 articles), and Bronze (15 articles). Based on all selection stages, 158 articles met the inclusion criteria and were used in the literature review.

Articles that met the selection criteria were then analyzed through a systematic data extraction and synthesis process. The information reviewed included publication characteristics, year of study, educational context, STEM learning approach used, scientific literacy aspects developed, and key findings from each study. The obtained data were then categorized and analyzed descriptively and thematically to identify research trends, STEM implementation patterns, the contribution of STEM learning to scientific literacy development, and any remaining research gaps. All stages of article identification, screening, eligibility evaluation, and inclusion are presented in a PRISMA flowchart (Figure 1) to provide a transparent overview of the literature selection process in this study.

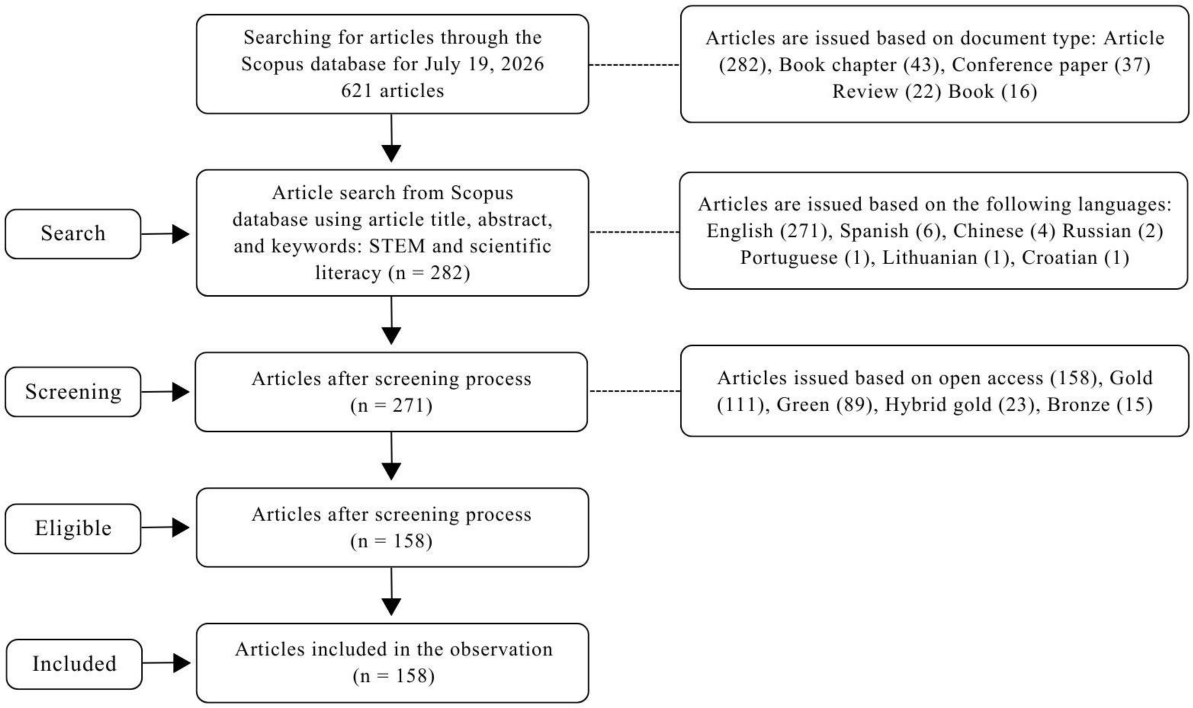

Figure 1. PRISMA Flow Diagram of the Study Selection Process

3. RESULTS AND DISCUSSION

3.1 Publication Development by Year

The development of publications by year indicates that research on STEM-based learning in early childhood education and children's scientific literacy has experienced a gradual increase over time. Based on Scopus data, publications in this field began to appear in 2008, although the number of documents remained relatively low and fluctuated until 2018. During this initial period, research attention toward STEM implementation in early childhood education was still limited, indicating that the integration of STEM concepts into early childhood contexts was still an emerging area of investigation. However, since 2019, a noticeable increase in publication output has occurred, demonstrating growing global interest in exploring STEM approaches as a means of developing children’s scientific literacy and supporting early scientific thinking development.

The increasing publication trend from 2019 onwards reflects the strengthening recognition of STEM-based learning as an important educational approach aligned with the demands of 21st-century competencies. The highest publication growth occurred in 2025, reaching approximately 36 documents, followed by a decline in 2026, which may be related to incomplete indexing of publications for the ongoing year. This upward trend demonstrates that STEM research in early childhood education is becoming an expanding interdisciplinary field involving education, science, technology, and child development perspectives. The continued growth of publications also highlights opportunities for future research, particularly in developing contextual STEM learning models through inquiry-based learning, play-based activities, exploration, project-based learning, and appropriate technology integration to strengthen children’s scientific literacy from an early age.

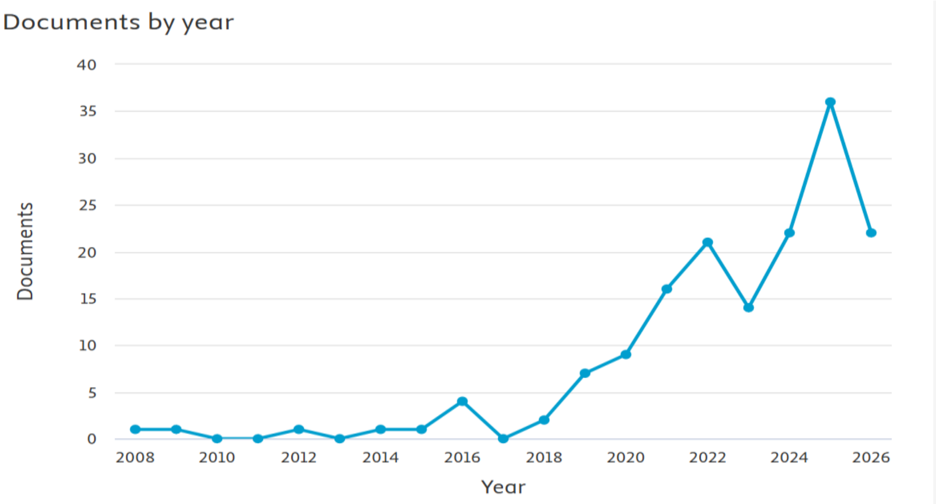

Figure 2. Research Development Based on Publication Year

3.2 Research Development by Country

Research development by country or territory indicates that studies on STEM-based learning in early childhood education and children’s scientific literacy have been conducted across various regions, although research contributions remain concentrated in several countries. Based on Scopus data, the United States represents the largest contributor with 64 documents, followed by Indonesia with 15 documents, Canada and Spain with 10 documents each, Germany and the United Kingdom with 6 documents each, and China, Malaysia, and Thailand with 5 documents each. This distribution demonstrates that research on STEM-based learning in early childhood education has gained international attention, but its development is still influenced by the research capacity and publication productivity of particular countries.

The dominance of the United States indicates its strong position in advancing STEM education research, particularly in areas related to learning innovation, curriculum development, and the enhancement of children's scientific literacy. Meanwhile, Indonesia’s contribution reflects the growing academic interest in implementing STEM approaches in early childhood education, particularly in response to curriculum transformation and the need to develop 21st-century competencies. However, the unequal distribution of publications among countries highlights the importance of strengthening international collaboration, cross-cultural research, and contextual STEM learning models that address diverse educational settings. These findings confirm that STEM-based learning and children’s scientific literacy represent an expanding global research field with considerable opportunities for further development.

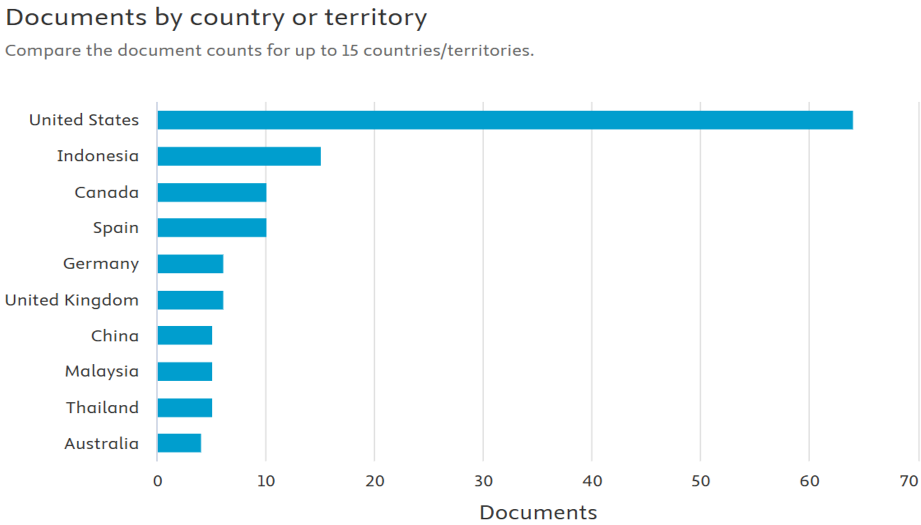

Figure 3. Documents By Country or Territory

3.3 Research Development Based on Number of Citations

An analysis of country contributions based on publication output and citation impact shows that research on STEM-based learning and children's scientific literacy has developed globally, with varying levels of productivity and scientific influence. The United States demonstrates the highest research productivity and impact, with 65 published documents and a total of 1.008 citations, indicating its leading position in the development of STEM studies in early childhood education. Indonesia follows with 15 documents and 255 citations, demonstrating its considerable contribution to the growth of research in this field. However, publication quantity does not always correspond directly with scientific impact, as shown by Spain, which produced 10 documents but received 391 citations, and Singapore, which produced only three documents but achieved 365 citations, indicating the high visibility and academic influence of their publications. Other countries, including Turkey (3 documents; 205 citations), Canada (10 documents; 179 citations), South Korea (3 documents; 149 citations), Ireland (1 document; 137 citations), Malaysia (5 documents; 124 citations), and the United Kingdom (6 documents; 82 citations), also contributed to the advancement of STEM-based learning and scientific literacy research. Overall, the distribution of publications and citations indicates that the development of this research field is determined not only by research productivity but also by the quality, visibility, and scientific influence of studies produced by each country.

Table 1. Documents by Citations

No.	Country	Documents	Citations	Total Link Strength
1	United States	65	1.008	0
2	Spain	10	391	0
3	Singapore	3	365	0
4	Indonesia	15	255	1
5	Turkey	3	205	0
6	Canada	10	179	0
7	South Korea	3	149	0
8	Ireland	1	137	0
9	Malaysia	5	124	0
10	United Kingdom	6	82	1

3.4 Research Developments Based on Cross-Country Collaboration Clusters

Based on bibliometric mapping results, the international collaboration network in research on STEM-based learning and children’s scientific literacy can be categorized into seven main clusters, reflecting patterns of scientific connectivity among countries. Cluster 1 includes Australia, Canada, China, Ethiopia, France, Ghana, and Romania, representing a broad cross-regional collaboration network involving countries from Asia, Europe, Africa, and Oceania. Cluster 2 consists of Croatia, Hungary, Ireland, Norway, Poland, and Serbia, indicating stronger regional collaboration patterns within Europe. Cluster 3 includes Chile, Finland, New Zealand, Spain, and Sweden, while Cluster 4 involves Argentina, Germany, Hong Kong, Mexico, and the United States, representing countries with relatively strong research productivity and scientific influence. The remaining clusters also demonstrate the existence of interconnected research networks across different geographical regions, although the intensity of collaboration varies among countries.

Overall, the cluster distribution indicates that research on STEM-based learning in early childhood education has developed within a global academic network, although collaboration patterns remain influenced by geographical proximity, institutional capacity, and existing research partnerships. Countries with stronger publication performance tend to occupy more central positions within the international research network, while several countries show opportunities to strengthen their connections through broader collaboration. For Indonesia, expanding international research partnerships may support the development of contextual STEM learning models that consider diverse educational and cultural settings. Strengthening cross-country collaboration is therefore important for advancing research innovation, particularly in areas such as digital STEM learning, pedagogical strategies, and approaches to fostering early childhood scientific literacy in alignment with 21st-century educational demands.

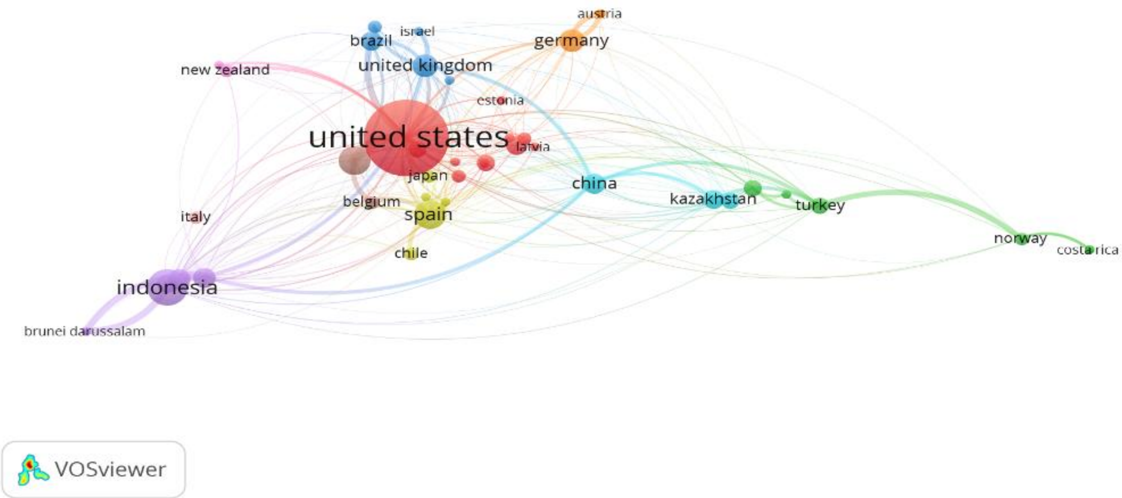

Figure 4. Visualization of Development Patterns Based on Clusters Among Countries

3.5 Research Development Based on Affiliation

Analysis of research productivity based on institutional affiliation shows that studies on STEM-based learning in early childhood education and children's scientific literacy involve contributions from various universities and research institutions worldwide, with a relatively distributed pattern of productivity. According to Scopus data, the University of Missouri represents the most productive institution with five publications, followed by Vanderbilt University with four publications. Other institutions, including Nanyang Technological University, Sechenov First Moscow State Medical University, University of Waterloo, University of California, Davis, Universidad de Burgos, University of California, San Diego, Plekhanov Russian University of Economics, and Moscow Aviation Institute, each contributed three publications. This distribution indicates that research development in STEM-based learning and children's scientific literacy is not concentrated within a single institution, but rather emerges from multiple academic communities with interests in STEM education, early childhood pedagogy, and science literacy development.

The contribution of institutions from the United States, Europe, and Asia demonstrates that research in this field has developed through an increasingly international academic network. However, the relatively similar publication output among leading institutions suggests that no single research center has yet become dominant in shaping the intellectual development of STEM-based learning in early childhood education. This condition provides opportunities for universities in various regions, particularly developing research communities, to strengthen international collaboration, conduct cross-cultural studies, and develop contextual STEM pedagogical innovations. Such efforts are important for producing learning models that support children's scientific literacy development while considering diverse educational contexts and the developmental characteristics of young learners.

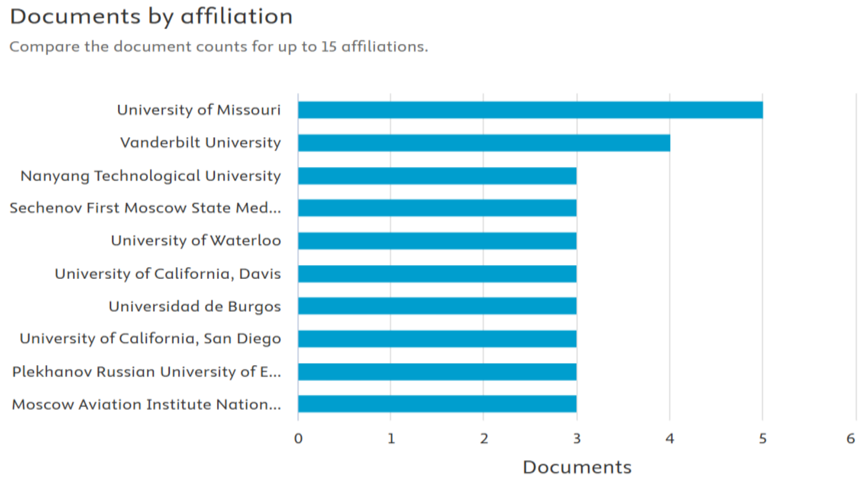

Figure 5. Document by Affiliation

3.6 Research Development Based on Journal Sources

Analysis of research development based on journal sources (source productivity) indicates that publications on STEM-based learning in early childhood education and children's scientific literacy have been disseminated across various international journals with different levels of productivity. According to Scopus data, *Education Sciences* represents the most productive source with 16 articles, followed by the *Journal of Microbiology and Biology Education* with 12 articles, *Frontiers in Education* with 7 articles, and the *International Journal of STEM Education* with 5 articles. Furthermore, *Disciplinary and Interdisciplinary Science Education Research* and the *Eurasia Journal of Mathematics, Science and Technology Education* each contributed 4 articles. The increasing publication trend in these journals, particularly from 2019 onwards, reflects growing academic attention toward STEM-based learning as an approach to support scientific literacy development in early childhood education.

The distribution of publications across various education, STEM, and science-related journals demonstrates that research in this field has developed within a multidisciplinary academic environment. The presence of STEM-focused and science education journals indicates that current research is increasingly concerned with how exploration, inquiry, problem-solving, project-based learning, and technology-supported activities can be adapted to young children's developmental characteristics. The absence of a single dominant journal source also suggests that this research area has a broad intellectual scope involving different educational perspectives and research communities. Therefore, STEM research in early childhood education is expected to continue developing alongside the growing demand for innovative learning approaches that foster scientific thinking skills and 21st-century competencies from an early age.

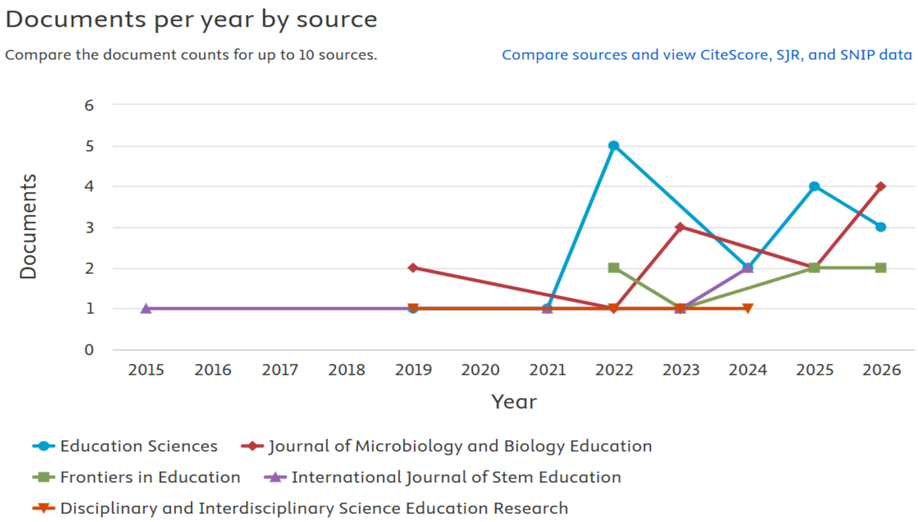

Figure 6. Annual Publication Trends by Source

3.7 Research Development Based on Authors

Analysis of research development based on author productivity shows that publications on STEM-based learning in early childhood education and children's scientific literacy involve contributions from diverse researchers, with no single author demonstrating a dominant level of productivity. According to Scopus data, Mercer, K., Ortiz-Revilla, J., Sadler, T.D., and Weaver, K.D. represent the most productive authors, each contributing three publications. Meanwhile, Aguiar, M., Aitbayeva, S., Araújo, S., Brito, M.A., Churchill, D., and Ellianawati each contributed two publications. This relatively balanced distribution indicates that research development in this field is supported by various scholars and research groups across different academic communities rather than being concentrated within a particular group of researchers.

The absence of authors with substantially higher publication outputs suggests that STEM-based learning research in early childhood education remains an open and expanding field with opportunities for broader scientific contributions. This pattern also reflects the multidisciplinary nature of the research area, involving perspectives from science education, early childhood pedagogy, curriculum development, and educational technology. Strengthening collaboration among researchers, institutions, and countries is therefore important to enhance theoretical development, expand empirical evidence, and support the design of effective STEM learning models that promote children's scientific literacy and scientific thinking skills.

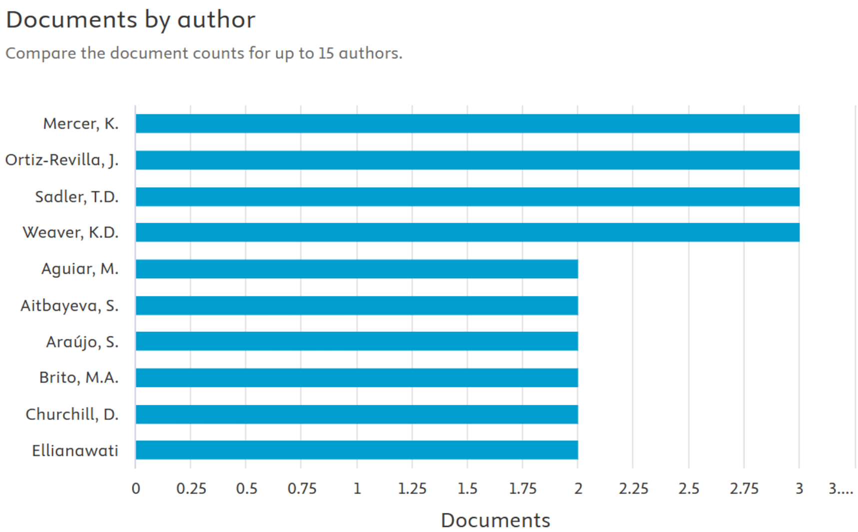

Figure 7. Annual Publication Trends by Author

3.8 Research Development by Subject Area

Analysis of research development by subject area shows that studies on STEM-based learning in early childhood education and children's scientific literacy are multidisciplinary. Social Sciences represents the largest proportion, accounting for 158 documents (47.3%), indicating a strong focus on education, pedagogy, child development, and learning processes. Furthermore, Computer Science contributed 30 documents (9.0%), followed by Psychology with 28 documents (8.4%), Biochemistry, Genetics, and Molecular Biology with 18 documents (5.4%), Health Professions with 17 documents (5.1%), Agricultural and Biological Sciences with 16 documents (4.8%), Immunology and Microbiology with 12 documents (3.6%), Engineering with 9 documents (2.7%), Mathematics with 7 documents (2.1%), and Arts and Humanities with 6 documents (1.8%), while other subject areas contributed 9.9%. This distribution demonstrates that research on STEM-based learning in early childhood education is not limited to pedagogical perspectives but also incorporates insights from technology, developmental psychology, health, and science to support the comprehensive development of children's scientific literacy. The dominance of Social Sciences confirms that education serves as the primary foundation for STEM implementation, while contributions from other disciplines highlight the interdisciplinary integration required to design contextual, innovative learning experiences aligned with the demands of 21st-century competencies.

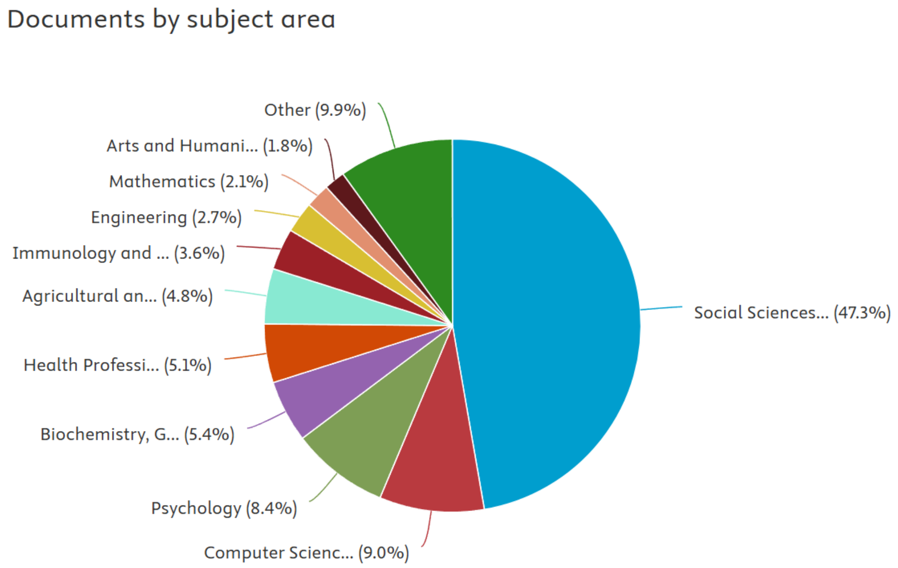

Figure 8. Distribution of Documents by Subject Area

3.9 Research Development Based on Keyword Co-occurrence Analysis

Based on keyword mapping using VOSviewer, seven main clusters were identified, representing the conceptual structure and thematic development of research related to STEM-based learning, early childhood education, and children's scientific literacy. The mapping results indicate that research in this field has developed as a multidisciplinary area, with two central themes, namely scientific literacy and STEM education, which are strongly connected with learning processes, curriculum development, teacher competency, educational technology, and 21st-century skills. Cluster 1 represents the theme of education and learning, characterized by keywords such as *education, student, curriculum, mathematics,* and *teaching*. This cluster indicates that research on scientific literacy is largely developed within the context of improving educational quality through curriculum innovation, instructional strategies, and learner development. In early childhood education, this theme reflects the importance of designing learning experiences that encourage children to explore, observe, and construct knowledge through meaningful activities.

Cluster 2 represents the central theme of STEM education, characterized by keywords such as *STEM, STEM education, science learning,* and *science literacy*. This cluster confirms that STEM-based learning is considered an important approach for developing children's scientific literacy through the integration of science, technology, engineering, and mathematics concepts in contextual learning experiences. The emergence of this theme demonstrates that STEM implementation is increasingly viewed not only as disciplinary integration but also as a strategy to develop children's curiosity, inquiry skills, problem-solving abilities, and scientific thinking from an early age.

Cluster 3 focuses on educator competency development, represented by keywords such as *teaching, improving classroom teaching,* and *science teacher initial training*. This cluster highlights that the effectiveness of STEM implementation is strongly influenced by teachers' knowledge, pedagogical competence, and readiness to design meaningful learning experiences. In early childhood education, teacher competency becomes an essential factor because STEM activities need to be adapted to children's developmental characteristics through play-based, inquiry-based, and exploration-oriented approaches.

Cluster 4 relates to the development of higher-order thinking skills, represented by keywords such as *critical thinking, biology,* and *science learning*. This cluster indicates that scientific literacy research is increasingly oriented toward developing children's abilities to analyze phenomena, solve problems, apply scientific concepts, and make connections between science and everyday experiences. Although early childhood learning emphasizes simple scientific experiences, these activities provide an important foundation for the gradual development of critical thinking and reasoning skills.

Cluster 5 illustrates the relationship between scientific literacy and sustainability issues through keywords such as *science literacy* and *sustainability*. This cluster shows that science education is not only focused on understanding scientific concepts but also contributes to developing awareness of environmental issues and sustainable practices. In early childhood contexts, sustainability-oriented STEM activities can be introduced through simple investigations related to nature, environmental care, and children's immediate surroundings.

Furthermore, Cluster 6 represents technology-based learning innovations through keywords such as *STEAM education, systems, science outreach,* and *Arduino*. This cluster demonstrates the increasing attention given to technology integration in STEM learning. However, in early childhood education, technology functions primarily as a supporting medium that enriches exploration and interaction rather than replacing hands-on experiences, direct observation, and play-based activities. Cluster 7 represents experiential learning and sustainable development, characterized by keywords such as *experiential learning* and *sustainable development*. This cluster emphasizes the importance of direct experiences, experimentation, and contextual activities in helping children develop meaningful scientific understanding.

Overall, keyword co-occurrence analysis demonstrates that research on STEM-based learning and children's scientific literacy has developed as an interdisciplinary field involving pedagogy, technology, teacher competency, creativity, sustainability, and experiential learning. The connections among clusters indicate a shift in science education research toward more contextual, collaborative, and experience-based learning approaches aimed at developing 21st-century competencies. In the context of early childhood education, these findings highlight the need for further research on how STEM approaches can be appropriately adapted to children's developmental stages to establish a strong foundation for scientific literacy from an early age.

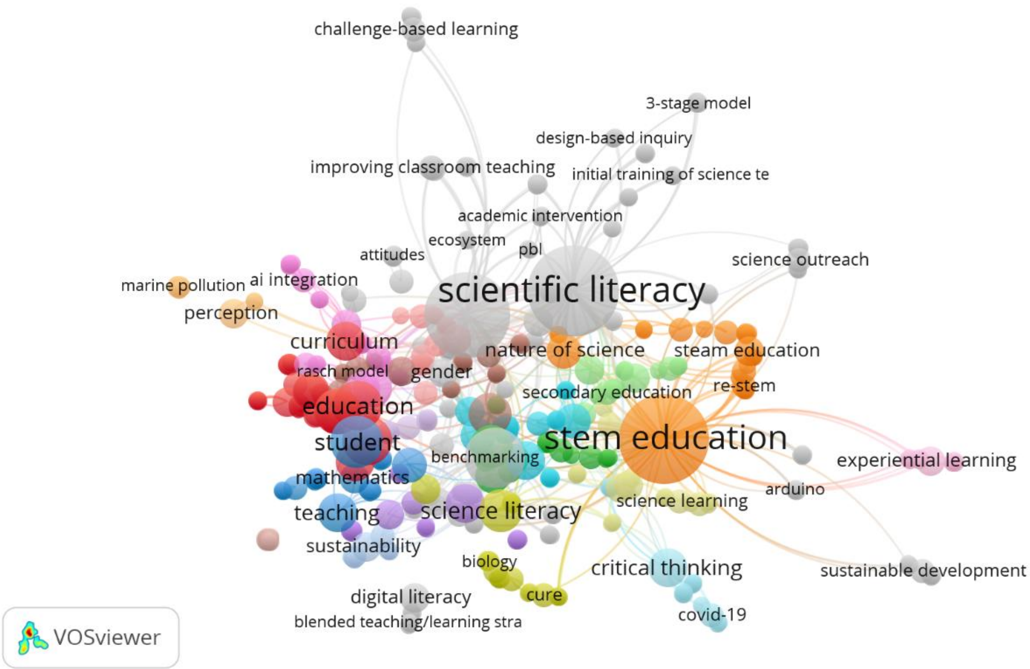

Figure 9. Visualization of Development Based on Keywords

3.10 Research Development Based on Keyword Link Strength

Based on Total Link Strength (TLS) analysis, this research identifies keywords that have the strongest level of connectedness in the bibliometric network. The TLS value represents the intensity of the relationship between a keyword and other keywords that appear simultaneously in scientific publications. Therefore, keywords with the highest TLS values can be understood as central concepts that have an important role in shaping the intellectual structure of the research field studied.

Table 2. Main Keywords Based on Total Link Strength

No.	Keyword	Total Link Strength
1	Stem Education	152
2	Scientific Literacy	136
3	Student	129
4	Stem	128
5	Science Education	80
6	Literacy	68
7	Schools	64
8	Teaching	57
9	Science	52
10	Science Literacy	48

Based on the TLS values presented in Table 2, the keyword "STEM education" has the highest level of connectivity with a TLS value of 152, indicating that it represents the central theme within the research network. This finding confirms that STEM education serves as the primary conceptual foundation linking various research topics related to scientific literacy development, science learning, curriculum, and educational practices. The keyword "scientific literacy" ranks second with a TLS value of 136, demonstrating its important role as a major research outcome associated with STEM implementation. Furthermore, the keywords "student" (129) and "STEM" (128) also show strong connectivity, indicating that research in this field focuses on learners as the main subjects and examines how STEM approaches contribute to the development of scientific understanding and literacy. The keyword "science education" with a TLS value of 80 further strengthens the relationship between STEM-based approaches and science learning processes. Meanwhile, keywords such as "literacy" (68), "schools" (64), and "teaching" (57) indicate that research development is closely related to educational contexts, instructional practices, and the implementation of STEM learning in formal learning environments. Other keywords, including "science" (52) and "science literacy" (48), further demonstrate the strong relationship between scientific concepts and literacy development. Overall, the Total Link Strength analysis confirms that research on STEM-based learning and children's scientific literacy has a multidimensional structure, integrating STEM education, science learning, curriculum development, teaching practices, and literacy development. These findings indicate that current research trends are increasingly oriented toward developing integrated and contextual STEM learning approaches to support scientific thinking skills and 21st-century competencies.

Global Trends in Research on STEM-Based Learning for Early Childhood Education

Based on bibliometric analysis, research on STEM-based learning in early childhood education has experienced significant growth in recent years, in line with increasing global attention to strengthening 21st-century competencies [5], [51], [57]-[59] through the development of scientific literacy from an early age [60], [61]. This development indicates that STEM is no longer viewed solely as an approach for secondary or higher education, but is beginning to become an essential part of building a foundation for scientific thinking from the earliest stages of child development [14]. STEM learning is now understood as a pedagogical approach that integrates science, technology, engineering, and mathematics through authentic learning experiences, thereby supporting the development of children's critical thinking, creativity, problem-solving, and inquiry skills [7], [8], [14], [62], [63].

Bibliometric analysis also shows that the contribution of STEM research is growing globally, with support from various countries focused on educational innovation, strengthening scientific literacy, and developing 21st-century skills [5], [51]. Differences in scientific influence across countries indicate that the contribution of research is determined not only by the number of publications, but also by the quality of the study, the relevance of the topic, and its contribution to the development of a particular scientific field [18], [64]. These findings demonstrate that research on STEM learning in early childhood has developed into an increasingly mature field of study and received widespread attention in the international academic community.

In addition to demonstrating the growth in the number of publications, keyword network analysis reveals that scientific literacy, education, science education, and students are dominant themes in STEM research, confirming that developing scientific literacy is one of the primary goals of implementing STEM learning [15], [51]. The dominance of these themes indicates that STEM research is fundamentally oriented toward how children gain scientific experience through the process of observing, exploring, investigating, and building an understanding of phenomena in their environment [60], [61].

The emergence of keywords such as engineering education, curriculum, STEM literacy, and augmented reality indicates the development of research towards a more integrated STEM curriculum design and the use of technology to support interactive learning experiences [14], [19]. This shift is in line with the constructivist approach which views children as active learners who build knowledge through direct experience, exploration, observation, and problem solving based on real contexts [22]. Thus, global research trends indicate that STEM-based learning not only plays a role in improving the understanding of scientific concepts, but also becomes an important strategy in building early childhood scientific literacy holistically through meaningful, contextual learning experiences, and oriented towards 21st-century skills [14], [33].

The Role of STEM-Based Learning in Developing Children's Scientific Literacy

STEM-based learning is an effective pedagogical approach for developing early childhood scientific literacy through active, contextual, and child-centered learning experiences [14], [39]. The integration of science, technology, engineering, and mathematics in exploration activities, simple experiments, problem-solving, and project-based learning can improve children's ability to observe phenomena, ask questions, construct simple explanations, and connect scientific concepts to everyday life [26], [39]. In addition to improving understanding of basic scientific concepts, the STEM approach also provides opportunities for children to develop curiosity, logical thinking skills, creativity, and scientific process skills through authentic and collaborative activities [21], [33]. These findings indicate that scientific experiences in childhood provide an important foundation for the development of scientific literacy at subsequent levels of education, as children build understanding through exploration, observation, and investigation of their surroundings [20], [21].

In addition to strengthening scientific literacy, STEM-based learning also contributes to the development of 21st-century competencies such as critical thinking, creativity, communication, collaboration, and problem-solving [5], [51]. STEM activities involving scientific investigation, engineering design, and problem-solving provide learning experiences that are appropriate to the developmental characteristics of early childhood while building scientific thinking skills from an early stage [39], [40]. The results of the study also show that the implementation of STEM is not only oriented towards mastering scientific concepts, but develops into an integrated approach that connects various disciplines through meaningful learning experiences [7], [14]. Thus, STEM-based learning is an important strategy in building early childhood scientific literacy holistically through exploratory, collaborative, and real-life experience-based activities [14], [33].

Characteristics of STEM Learning Implementation in Early Childhood

The characteristics of STEM-based learning implementation in early childhood education can be grouped into three main themes: scientific literacy development, STEM curriculum integration, and technology utilization in learning [14], [34]. The first theme relates to scientific literacy development, as indicated by the dominance of keywords such as "student," "scientific literacy," "education," and "science education." This dominance indicates that STEM research in early childhood places children at the center of learning, focusing on the ability to observe, explore, ask questions, conduct simple investigations, and communicate the results of observations [21], [22], [65]. Scientific literacy development in STEM learning is not achieved through direct conceptualization, but through play activities, environmental exploration, simple experiments, and inquiry-based learning that align with the developmental characteristics of early childhood [14], [20], [22], [31]. This approach reinforces the constructivist view that children construct knowledge through direct experience and active interaction with the learning environment [66].

The second theme relates to the integration of the STEM curriculum, demonstrated through the interrelationship between the concepts of STEM education, engineering education, curriculum, and STEM literacy. The implementation of STEM in early childhood education is not understood as teaching four separate disciplines, but as an integrated approach that connects science, technology, engineering, and mathematics in contextual learning experiences [7], [14], [67]. Various studies have shown that approaches such as play-based learning, project-based learning, and the engineering design process are effective in developing children's creativity, critical thinking, collaboration, and problem-solving skills [26], [39], [40]. The third theme shows the increasing use of technology in STEM implementation. The emergence of digital technology and interactive media shows that cutting-edge research is beginning to integrate various technological devices to enrich children's learning experiences [68]. However, technology remains seen as a supporting tool, while exploration, investigation, and hands-on experience remain the core of STEM learning in early childhood [24], [32]. Thus, the characteristics of the implementation of STEM learning in early childhood education are not only characterized by multidisciplinary integration, but also by authentic, collaborative, exploration-based learning experiences, and oriented towards the development of holistic scientific literacy [14], [34].

STEM-Based Learning Concepts to Improve Children's Science Literacy

Based on a synthesis of 158 analyzed articles, this study developed a conceptual framework that illustrates the relationship between the learning support ecosystem, the implementation of STEM pedagogy, authentic learning experiences, the development of science literacy, and the achievement of 21st-century competencies in early childhood. This framework demonstrates that science literacy does not develop in isolation but rather is the result of the interaction of various mutually supportive components, including teacher competency, STEM curriculum integration, the learning environment, technology utilization, and family involvement. These factors facilitate the implementation of various STEM-based learning approaches, such as play-based learning, inquiry-based learning, project-based learning, engineering design processes, and collaborative learning, which result in authentic learning experiences through exploration, observation, experimentation, investigation, reflection, and problem-solving. These learning experiences further contribute to the development of the main dimensions of children's scientific literacy, which include scientific knowledge, scientific process skills, scientific attitudes, scientific reasoning, and scientific communication, and serve as a foundation for the development of 21st-century competencies, such as critical thinking, creativity, collaboration, communication, and readiness for STEM learning at subsequent levels of education. The resulting conceptual framework is presented in the following figure 10.

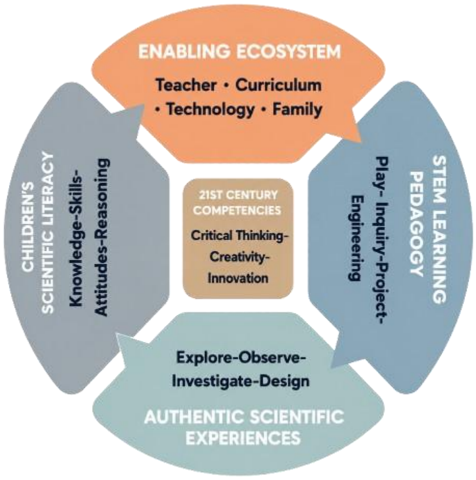

Figure 10. Conceptual Framework of STEM-Based Learning to Improve Early Childhood Science Literacy

4. CONCLUSION

This systematic review provides a comprehensive overview of global research developments on STEM-based learning in improving early childhood scientific literacy through the integration of bibliometric analysis and thematic synthesis. The results show a significant increase in the number of publications over the past few years, reflecting the growing attention of the scientific community to STEM learning as a strategy for developing scientific literacy from an early age. The bibliometric analysis indicates that scientific literacy, STEM education, science education, curriculum, and engineering education are the most dominant themes in the research landscape, indicating a shift in research direction toward more integrated, inquiry-based, and child-centered learning. The thematic synthesis also shows that the implementation of STEM learning in early childhood education is generally realized through play, exploration, simple experiments, and problem-solving activities that enable children to construct scientific understanding through authentic and contextual learning experiences. Thus, STEM learning is no longer understood as merely integrating the four disciplines, but as a pedagogical approach capable of developing scientific literacy while strengthening creativity, critical thinking, collaboration, communication, and 21st-century competencies from an early age. The findings of this study have important implications for research, educational practice, and policy development. From a research perspective, further studies should examine the long-term impact of STEM implementation on the development of children's scientific literacy, teacher competency, family engagement, and the use of digital technology appropriate to the characteristics of early childhood education. Research in developing countries also needs to be expanded to generate more diverse and contextual empirical evidence. From an educational practice perspective, teachers need support in designing STEM-based learning experiences that are child-centered, play-based, and encourage meaningful exploration, investigation, and problem-solving. Meanwhile, from a policy perspective, strengthening STEM integration in early childhood education curricula, improving teachers' professional competencies, and providing adequate learning resources are needed to ensure the sustainable implementation of STEM learning. Overall, this systematic review confirms that STEM-based learning is a promising approach to improving early childhood scientific literacy while building the foundation for scientific thinking skills and 21st-century competencies needed to navigate an increasingly knowledge- and technology-driven society.

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AUTHOR CONTRIBUTIONS

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CONFLICTS OF INTEREST

The author(s) declare no conflict of interest.

INFORMED CONSENT STATEMENT

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USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declare that no artificial intelligence (AI) tools were used in the generation, analysis, or writing of this manuscript. All aspects of the research, including data collection, interpretation, and manuscript preparation, were carried out entirely by the authors without the assistance of AI-based technologies.

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