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Research Trends in Science Literacy in Education: A Bibliometric Analysis for the Period 2022-2025

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Abstract

Scientific literacy has become a key competency in contemporary science education, particularly amid the post-pandemic landscape marked by accelerating digitalization, expanding access to information, and growing demand for evidence-based decision-making. Although literature on scientific literacy continues to expand, understanding of recent research developments remains limited. This study aims to examine research trends, intellectual structures, and emerging themes in scientific literacy research within educational contexts from 2022-2025. A bibliometric approach was adopted using data retrieved from the Scopus database through a systematic search and screening process guided by the PRISMA framework, with publications analyzed via Microsoft Excel and VOSviewer to assess publication growth, geographical and institutional contributions, citation performance, and keyword co-occurrence networks. The results indicate a substantial increase in publication output after 2023, with the United States, Indonesia, and China as leading contributors, reflecting the global scope of the field and disparities in national research capacities. Institutional analysis reveals broad participation across universities and research organizations, while citation and keyword analyses point to inquiry-based learning, scientific reasoning, critical thinking, and emerging themes including socioscientific issues and technology-enhanced education. These findings signal a shift toward competency-based frameworks emphasizing reasoning and evidence evaluation, informing curriculum development and future research.

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INTRODUCTION

Scientific literacy is a crucial component in facing the challenges of the 21st century. Scientific literacy is an indicator used to assess the quality of a country's education (Osborne & Allchin, 2025). The Organisation for Economic Co-operation and Development (OECD) uses the Programme for International Student Assessment (PISA) to measure students' scientific literacy skills across countries (Ustun et al., 2022). Scientific literacy is a person's ability to utilize scientific knowledge, ask questions, and draw conclusions based on evidence to understand natural phenomena and changes resulting from human activity (Fortus et al., 2022). Scientific literacy has become an important concept in education and is widely recognized as a primary goal of the educational process.

In recent years, the concept of scientific literacy has expanded beyond the traditional understanding of scientific concepts and processes. In the digital era, scientific literacy also encompasses the ability to critically evaluate information, distinguish scientific evidence from misinformation, and make informed decisions regarding complex socio-scientific issues. The rapid growth of digital media and artificial intelligence has increased public exposure to scientific information while simultaneously increasing the spread of inaccurate or misleading content. Consequently, educational systems are expected not only to improve students' conceptual understanding but also to develop critical reasoning, evidence evaluation, and responsible decision-making skills that enable learners to participate effectively in contemporary society (Murtadho et al., 2023).

Based on the results of the 2022 PISA, the average scientific literacy score of students from OECD member countries was 485 (OECD, 2023; Osborne & Pimentel, 2023). This score is used as a benchmark for assessing students' scientific literacy performance in developed countries. Countries that score $\geq$ 485 are categorized as having good to excellent levels of scientific literacy (Saija et al., 2022). This indicates that the science learning system in that country is relatively effective in developing students' scientific literacy skills. However, conditions on the ground show that students' scientific literacy skills in several countries, including Indonesia, are still suboptimal (Romero Ariza et al., 2024).

In 2022, PISA measurements were conducted, showing that Indonesian students' scientific literacy scores were 383 points, a decrease from 396 points in 2018, and still far below the OECD average of 485 points (Valio et al., 2025). Although Indonesia's ranking improved by six positions compared to the 2018 PISA, it remained in the bottom group. This indicates that students' scientific literacy skills in Indonesia still need to be improved (Ivanka et al., 2025).

Improving scientific literacy is not only essential for enhancing students' academic achievement but also for preparing future citizens capable of addressing global challenges such as climate change, environmental sustainability, public health, and technological innovation. Individuals with strong scientific literacy are better equipped to interpret scientific evidence, evaluate risks, and participate in evidence-based decision making. Therefore, strengthening scientific literacy has become an educational priority in many countries because it contributes directly to sustainable development and lifelong learning (Ustun et al., 2022; Valio et al., 2026).

Consistent with this, Hartono et al. (2023) showed that students' scientific literacy levels in genetics were still relatively low, at 32.63%, 42.97%, and 43.06% in the three classes studied. This low ability is caused by several factors, such as the use of inappropriate textbooks, student misconceptions about science material, and learning that is not yet contextualized to students' lives. This low scientific literacy is also in line with the various obstacles experienced by students in learning. According to Azizah et al. (2015), as many as 76% of students experience difficulty in solving problems, which is a core concept of scientific literacy. More specifically, approximately 26% of students experienced difficulty understanding concepts, and 17% experienced difficulty understanding and analyzing graphs and images. This indicates that students' scientific literacy skills are still not optimal, so efforts are needed to improve the quality of learning that can develop these skills (Toomey, 2023).

Indonesia's low scientific literacy score has become a concern for academics and practitioners, and the number of studies addressing this topic continues to increase year after year (Ramli & Susanti, 2022). Various studies have been conducted with diverse focuses, such as the development of learning models, the use of technology in science learning, and the analysis of students' scientific literacy skills (Mafarja et al., 2025).

Existing studies have primarily focused on evaluating students' scientific literacy levels, developing instructional models, integrating digital technology into science learning, and assessing the effectiveness of inquiry-based or problem-based learning approaches. Although these stud-

ies have generated valuable findings, they generally investigate specific educational interventions or particular student populations. Consequently, the broader development of scientific literacy research at the international level has not been comprehensively synthesized. A comprehensive understanding of publication trends is important because it enables researchers to identify dominant research themes, emerging topics, influential countries and institutions, as well as potential research gaps that require further investigation. Such information is valuable for researchers, educators, and policymakers when determining future research priorities and designing educational strategies that are aligned with global developments (Li & Guo, 2021).

However, this abundance of research does not provide a clear picture of the development of research trends, dominant topics, and research directions in the field of scientific literacy. Post-COVID-19 pandemic, particularly since 2022, the education system has undergone various changes, such as the implementation of technology-based learning, in-depth learning, and adjustments to learning strategies. These changes also have the potential to influence the direction of research related to scientific literacy (Kamrozzaman & Mohan, 2025). Therefore, it is important to understand how scientific literacy research has developed in the educational context in the post-pandemic period. Bibliometric analysis can be used to systematically analyze research developments. Bibliometric analysis is a method used to quantitatively analyze scientific publications, thus providing an overview of research trends, collaboration patterns, and emerging topics within a particular field. According to Ellegaard and Wallin (2015), bibliometric analysis can be used to identify and categorize various aspects of a scientific field, including the most contributing authors, journals, institutions, universities, and countries (Vengadesh et al., 2023).

Based on the above description, it can be seen that although numerous studies related to scientific literacy have been conducted, studies specifically mapping trends in scientific literacy research in education, particularly in the post-pandemic period, remain limited. Therefore, research that can provide a more comprehensive overview of the development of this field is needed. Bibliometric analysis provides a systematic and objective approach for evaluating the evolution of scientific knowledge within a particular research field. Unlike traditional literature reviews, bibliometric techniques enable researchers to quantitatively identify publication growth, collaboration patterns, influential publications, thematic relationships, and emerging research directions based on large bibliographic datasets. Therefore, applying bibliometric analysis offers a comprehensive overview of how scientific literacy research has evolved during the post-pandemic period and provides evidence that can guide future educational research and policy development. This study aims to analyze trends in scientific literacy research in education and identify dominant topics based on scientific publications from 2022 to 2025 using a bibliometric approach.

METHOD

This study used a bibliometric analysis approach to analyze scientific publications related to scientific literacy in education, specifically science education (Tosun, 2024). This approach allows researchers to quantitatively evaluate the number of publications, research trends, and collaboration patterns among authors, institutions, and countries that contribute to the field (Ninkov et al., 2021). The bibliometric analysis aims to map the distribution of publications, identify dominant topics, and understand the relationships between elements in the literature that focuses on scientific literacy in the post-pandemic educational context. This approach was chosen because it provides a comprehensive overview of research trends, scientific collaborations, and the distribution of publications by region and academic institutions (Lazarides et al., 2023).

Scopus was used for data collection, given its reputation as one of the leading scientific databases providing globally indexed scientific articles (Al-Khoury et al., 2022). The data collection process was conducted systematically. Data retrieval took place on April 22, 2026, at 7:30 PM WIB (Western Indonesian Time) using a title-abstract-keyword search with the query: (”scientific literacy”) AND (”science education”) AND (”student” OR ”secondary school” OR ”high school”).

The initial search results were filtered to ensure that only relevant articles were analyzed. The data filtering process was performed using several criteria. First, only journal articles were selected for inclusion. Second, only final and published documents were included in the review. Third, only articles published in English were selected. Fourth, the publication year range was limited to 2022–2025 to capture research trends during the post-pandemic period. Furthermore, filtering was conducted based on the social scien-

ces field to ensure suitability for the educational context. This process aims to ensure that the data used are of high quality and have clear relevance to the research topic.

The search query used in this study was as follows:
("scientific literacy") AND ("science education") AND ("student" OR "secondary school" OR "high school") AND PUBYEAR > 2020 AND PUBYEAR < 2026 AND (LIMIT-TO (SUBJAREA, "SOCI")) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (EXACTKEYWORD, "Scientific Literacy") OR LIMIT-TO (EXACTKEYWORD, "Students") OR LIMIT-TO (EXACTKEYWORD, "Science Education")) AND (LIMIT-TO (PUBSTAGE, "final")) AND (LIMIT-TO (LANGUAGE, "English")).

Furthermore, the article selection process was carried out following the PRISMA stages to ensure transparency and systematic data selection (Vu-Ngoc et al. 2018). After the screening process, the final data obtained were used for further analysis.

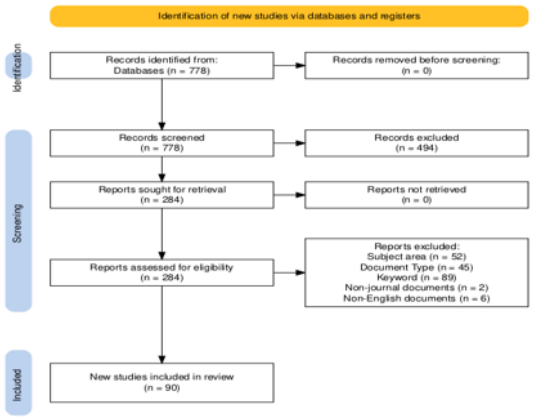

Figure 1. PRISMA Diagram

For data analysis and visualization, we used VOSviewer, and Microsoft Excel software. VOSviewer was used to map the keyword co-occurrence networks, co-authorship collaborations, and citation relationships between publications (Muktiarni et al., 2023). Co-occurrence analysis was used to identify frequently occurring keywords, co-authorship analysis to examine collaboration patterns between researchers, and citation analysis to determine the most influential publications in the field (Hassan & Duarte, 2024). Microsoft Excel was used to manage the data, graph publication trends, and perform a simple frequency analysis (Divisi et al., 2017). To ensure data quality, a data cleaning process was performed to reduce inconsistencies, such as data duplication and variations in keyword spelling using a thesaurus. This process aims to make the analyzed data more accurate and can produce more valid interpretations of the data. The combination of methods and software used allows for a more comprehensive and structured analysis of the data (McAllister et al., 2021).

This study applied the inclusion criteria to ensure that only relevant and high-quality articles were analyzed. The selected articles had to be final, written in English, and discuss scientific literacy in an educational context. The primary focus of this study was on publications that examined trends, topics, and developments in scientific literacy research, particularly in the post-pandemic period.

RESULT AND DISCUSSION

Distribution of Publications by Year

The annual distribution of publications on scientific literacy in education between 2022 and 2025 is presented in Figure 2. The data reveal a generally increasing trend in the number of publications over the observed period, indicating a growing academic interest in scientific literacy as a critical area of educational research. Although a slight decline was observed during the early years of the period, publication output increased substantially in the following years, suggesting renewed and sustained scholarly attention to this topic. This upward trajectory reflects the increasing recognition of scientific literacy as a fundamental competency required for learners to navigate complex scientific, technological, and societal issues in the modern world.

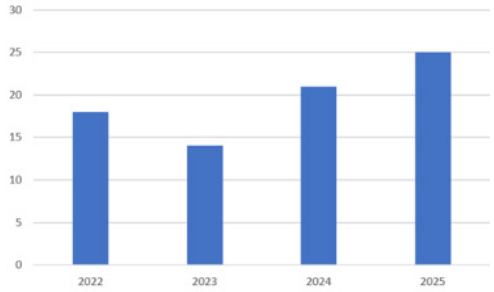

Figure 2. Development of the Number of Publications

The growing volume of publications can be attributed to significant transformations in education following the COVID-19 pandemic. The rapid integration of digital technologies into teaching and learning environments has altered how students access, evaluate, and interpret scientific information. In this context, scientific literacy has become increasingly important because it

equips individuals with the ability to understand scientific concepts, critically assess evidence, and make informed decisions in both personal and societal settings. As emphasized by Osborne and Allchin (2025), scientific literacy extends beyond the acquisition of factual scientific knowledge and encompasses the capacity to engage with scientific reasoning, evaluate claims based on evidence, and apply scientific understanding to real-world problems.

Furthermore, the continued growth in publication output highlights the expanding scope and diversity of scientific literacy research. Recent studies have focused on innovative pedagogical approaches designed to enhance students' scientific understanding and higher-order thinking skills. These approaches include inquiry-based learning, problem-based learning, contextual learning, STEM-oriented instruction, and technology-enhanced educational practices. Researchers have increasingly investigated how these instructional models can foster critical thinking, scientific reasoning, argumentation skills, and the ability to solve authentic problems. Such developments reflect a broader shift in science education from traditional content-centered instruction toward competency-based learning frameworks that emphasize the practical application of knowledge and the development of transferable skills (Kamrozzaman & Mohan, 2025; Valio et al., 2025).

Overall, the publication trend observed in this study demonstrates not only an increase in research productivity but also a significant evolution in educational priorities. The growing emphasis on scientific literacy reflects global efforts to prepare learners for the challenges of the twenty-first century, where scientific understanding, critical evaluation of information, and evidence-based decision-making are increasingly essential for active participation in society.

Distribution of publications based on authors from a country

Figure 3 illustrates the geographical distribution of scientific literacy publications based on the corresponding author's country during the 2022–2025 period. The findings reveal that scientific literacy research has attracted widespread attention across different regions of the world, with contributions originating from a diverse range of countries. However, the distribution of publications is not evenly balanced. A relatively small number of countries account for a substantial proportion of the total research output, while many others contribute at a comparatively lower level. This pattern suggests that although scientific literacy has emerged as a global educational research theme, publication productivity remains concentrated in countries possessing stronger research ecosystems, more developed higher education systems, and greater investment in educational research.

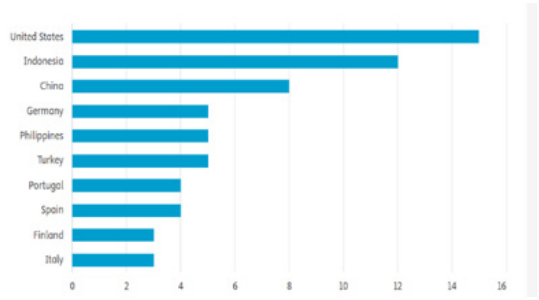

Figure 3. Publications by Country

The observed geographical distribution reflects the close relationship between research productivity and national research capacity. Countries with advanced research infrastructures generally have greater access to funding opportunities, well-established academic institutions, experienced researchers, and extensive international collaboration networks. These factors facilitate the production of high-quality scientific publications and enhance the visibility of research outputs in international journals. In addition, government policies that prioritize educational improvement and innovation often encourage scholarly investigations into scientific literacy, particularly in response to growing concerns about students' preparedness for science-related challenges in contemporary society.

Another important factor influencing publication trends is participation in international educational assessment programs, particularly the Programme for International Student Assessment (PISA). The increasing emphasis on scientific literacy within PISA has encouraged policymakers, educators, and researchers to examine factors affecting students' scientific competencies and to develop evidence-based strategies for educational improvement. Consequently, scientific literacy has become a key research focus in many countries seeking to enhance educational quality, strengthen critical thinking skills, and improve students' performance in international benchmarks (OECD, 2023). The widespread use of PISA results as indicators of educational achievement has further stimulated comparative and policy-oriented research on scientific literacy across different national contexts.

The prominent contribution of Indonesia

identified in this bibliometric analysis reflects the growing commitment of Indonesian scholars to advancing scientific literacy research. This trend is likely associated with ongoing educational reforms, curriculum development initiatives, and increasing awareness of the importance of preparing students for a knowledge-based society. Indonesian researchers have increasingly explored innovative pedagogical approaches, including inquiry-based learning, STEM education, digital learning environments, and contextual learning strategies aimed at enhancing students' scientific reasoning and problem-solving abilities. Similar developments have been reported in other countries, where scientific literacy research has expanded to incorporate emerging themes such as socioscientific issues, sustainability education, and technology-enhanced learning environments (Silmiah et al., 2025; Fernández-Huetos et al., 2026).

Overall, the geographical distribution of publications confirms that scientific literacy has evolved into a significant global research agenda within the field of education. Nevertheless, the unequal distribution of research productivity indicates the need for stronger international collaboration, particularly between highly productive and emerging research countries. Expanding collaborative networks can facilitate knowledge exchange, strengthen research capacity, promote methodological diversity, and support the development of evidence-based educational innovations. Such efforts are expected to contribute to a more comprehensive understanding of scientific literacy while reducing disparities in global educational research and fostering more inclusive scientific knowledge production worldwide.

Articles in Citations

Figure 4 presents the ten most highly cited publications in scientific literacy research published during the 2022–2025 period. Citation analysis serves as an important bibliometric indicator for identifying influential studies that have significantly contributed to the development of a research field. The results reveal that a relatively small number of publications account for a substantial proportion of total citations, indicating that several studies have emerged as key references for researchers investigating scientific literacy in educational contexts. This pattern is consistent with the nature of scientific knowledge development, where influential publications often provide conceptual foundations, methodological advancements, or innovative educational practices that guide subsequent research. The concentration of citations among a limited number of articles suggests that these studies have played a critical role in shaping contemporary discussions and research directions within science education.

Figure 4. Ten scientific articles with the highest number of citations

The highly cited publications identified in this analysis predominantly focus on themes related to instructional innovation, scientific reasoning, inquiry-based learning, critical thinking, and the development of students' scientific literacy competencies. These research areas have gained increasing prominence because educational systems worldwide are facing the challenge of preparing learners to engage effectively with complex scientific information in an era characterized by rapid technological advancement and widespread access to information. As highlighted by Osborne and Allchin (2025), scientific literacy extends beyond understanding scientific concepts and includes the ability to evaluate evidence, interpret scientific claims, and apply scientific reasoning to real-world situations. Consequently, studies that propose effective strategies for fostering these competencies have attracted considerable attention from scholars and practitioners alike.

Another noteworthy finding is that many of the most influential publications were produced within a relatively short time frame yet have already accumulated substantial citation counts. This observation suggests that scientific literacy has become a rapidly evolving field of research characterized by strong academic interest and high relevance to contemporary educational challenges. The accelerated growth of digital learning environments, increasing emphasis on evidence-based decision-making, and the need to combat misinformation have further elevated the importance of scientific literacy research. As a result, publications that address these emerging issues through innovative pedagogical approaches, technology-enhanced learning strategies, and

interdisciplinary perspectives are more likely to gain visibility and influence within the scholarly community (Valio et al., 2025).

Nevertheless, citation performance should be interpreted with caution. Citation counts are influenced by multiple factors beyond the intrinsic quality of a study, including publication age, journal reputation, indexing coverage, accessibility, international collaboration networks, and the popularity of specific research topics. Articles published in high-impact journals or addressing widely discussed educational issues often receive greater visibility and, consequently, higher citation rates. Therefore, citations should be viewed as indicators of scholarly influence rather than definitive measures of research excellence.

Overall, the citation analysis demonstrates that scientific literacy research is increasingly shaped by studies emphasizing meaningful learning, educational innovation, interdisciplinary approaches, and the development of higher-order thinking skills. These influential publications not only contribute to the theoretical advancement of the field but also provide practical guidance for educators and policymakers seeking to enhance scientific literacy in diverse educational settings. Consequently, they continue to serve as important foundations for future research and educational reform initiatives in science education (Osborne & Pimentel, 2023).

Institutions that contribute the most to research

Figure 5 illustrates the institutional distribution of scientific literacy research published between 2022 and 2025. The results show that contributions originate from a diverse range of universities and research institutions, with no single institution exhibiting a dominant position in terms of publication output. This pattern indicates that scientific literacy has evolved into a widely recognized research area that attracts scholarly attention across different academic environments and geographical regions. The broad distribution of publications suggests that scientific literacy is no longer confined to a small group of specialized research centers but has become an important topic within the global educational research community.

The relatively balanced institutional productivity observed in this study reflects the interdisciplinary and multifaceted nature of scientific literacy research. Scientific literacy encompasses not only the understanding of scientific concepts but also the development of critical thinking, problem-solving skills, evidence evaluation, and informed decision-making. Consequently, research in this field draws upon multiple disciplines, including science education, curriculum development, educational psychology, teacher education, assessment studies, and educational technology. Because of this interdisciplinary character, institutions with diverse academic strengths can contribute meaningfully to the advancement of scientific literacy through different theoretical, methodological, and practical perspectives. As noted by Saputra et al. (2026), the integration of various educational disciplines has become an important driver of innovation in scientific literacy research, enabling researchers to address complex educational challenges from complementary viewpoints.

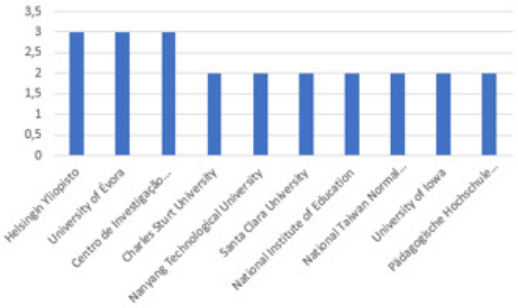

Figure 5. Most Relevant Affiliations

The findings also highlight the growing importance of collaboration among universities and research organizations. In contemporary educational research, collaborative networks have become essential mechanisms for knowledge production and dissemination. Cross-institutional collaboration enables researchers to share expertise, access broader datasets, employ diverse methodological approaches, and generate findings with greater generalizability. Such cooperation is particularly valuable in scientific literacy research because educational contexts, curriculum structures, and learning environments vary considerably across countries and regions. Through collaborative investigations, researchers can compare educational practices, identify common challenges, and develop context-sensitive strategies for improving students' scientific literacy competencies. Previous studies have emphasized that international and inter-institutional partnerships contribute significantly to enhancing research quality and promoting the adoption of evidence-based educational innovations (Li & Guo, 2021).

Despite the balanced distribution of institutional contributions, strengthening international research networks remains a critical priority for future development. Increased collaboration

among universities, research centers, governmental agencies, and educational organizations can accelerate the advancement of scientific literacy research by fostering innovation, improving methodological rigor, and expanding the dissemination of research findings. Furthermore, collaborative initiatives may support the development of standardized assessment frameworks, technology-enhanced learning models, and evidence-based educational policies aimed at improving scientific literacy outcomes globally. Therefore, the institutional distribution identified in this study not only reflects the growing popularity of scientific literacy as a research topic but also demonstrates the substantial potential for future international cooperation and knowledge exchange within the field of science education.

Number of Keyword occurrences

Figure 6 presents the keyword co-occurrence network of scientific literacy research published between 2022 and 2025. The visualization identifies scientific literacy as the central and most interconnected keyword, linking closely with several prominent themes such as science education, students, inquiry-based learning, nature of science, teacher education, and critical thinking. The dense network structure indicates that scientific literacy research has expanded beyond a narrowly defined area of study and has developed into a broad and interconnected field encompassing multiple dimensions of science education. The strong relationships among keywords suggest that researchers increasingly view scientific literacy as a complex educational construct that requires the integration of cognitive, pedagogical, social, and contextual perspectives.

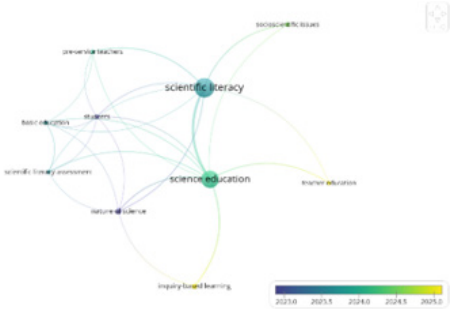

Figure 6. Frequently occurring keywords

The prominence of keywords associated with inquiry-based learning, science education, and students reflects a growing emphasis on developing scientific reasoning and higher-order thinking skills. Contemporary educational research increasingly recognizes that scientific literacy extends beyond the acquisition of scientific facts and concepts. Instead, it involves learners' ability to critically evaluate scientific evidence, construct evidence-based arguments, solve real-world problems, and make informed decisions regarding issues that affect society and the environment. The close association among these keywords supports the argument that effective science education should cultivate not only conceptual understanding but also the competencies required for active participation in an increasingly science- and technology-driven society (Osborne & Allchin, 2025). Consequently, instructional approaches that promote inquiry, investigation, and argumentation have become central themes in scientific literacy research.

Another notable finding is the appearance of keywords related to digital learning, technology-enhanced education, and socioscientific issues. Their presence indicates that scientific literacy research is responding to emerging educational challenges associated with the rapid growth of digital information and technological innovation. In contemporary society, students are exposed to vast amounts of scientific information through online platforms, social media, and digital communication channels. As a result, scientific literacy increasingly involves the ability to assess the credibility of information sources, identify misinformation, and interpret scientific claims critically. Furthermore, the inclusion of socioscientific issues highlights the growing importance of connecting science learning with real-world challenges such as climate change, public health, sustainability, and technological ethics . These developments align with recent studies emphasizing contextual and inquiry-based learning approaches as effective strategies for strengthening students' scientific literacy and engagement with science-related issues (Kamrozzaman & Mohan, 2025; Valio et al., 2025).

The analysis also reveals variations in terminology, particularly the frequent use of both scientific literacy and science literacy to describe closely related concepts. Although these terms are often used interchangeably in the literature, inconsistencies in terminology may affect keyword mapping and bibliometric visualization by fragmenting conceptually similar research into separate clusters. Greater standardization of terminology would improve the accuracy of bibliometric analyses and facilitate more reliable comparisons across studies and educational contexts (Osborne & Pimentel, 2023).

Overall, the keyword co-occurrence network demonstrates a significant shift in scientific

literacy research from a traditional focus on knowledge acquisition toward a competency-based framework that integrates scientific reasoning, critical thinking, digital literacy, and responsible decision-making. This evolution reflects changing educational priorities and highlights the increasing importance of interdisciplinary, context-based, and technology-supported approaches for preparing learners to address complex scientific and societal challenges in the twenty-first century.

CONCLUSION

Based on a bibliometric analysis of publications from 2022 to 2025, this study concludes that the trend of scientific literacy research in education has shown significant improvement, particularly after the COVID-19 pandemic. This is indicated by the increasing number of publications, evolving focus of studies, and expansion of contributions from various countries and institutions. Research topics are dominated by the relationship between scientific literacy and science education, with an emphasis on the role of students, inquiry-based learning approaches, technology integration, and strengthening critical thinking and problem-solving skills in real contexts. Furthermore, the research findings indicate that scientific literacy is understood not only as a cognitive ability but also as a multidimensional competency relevant to social issues and current developments. Although research contributions have been global, international collaboration and the standardization of terminology still need to be improved. Therefore, future research should focus more on the integration of innovative learning strategies, comprehensive evaluation, and strengthening contextual relevance to support the development of sustainable and adaptive scientific literacy to meet the challenges of 21st-century education.

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