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Science Literacy and Its Impact on Scientific Knowledge Acquisition: A Review of Current Research and Practices

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Abstract: This bibliometric and thematic review synthesizes global research on science literacy and its influence on scientific knowledge acquisition from 2016 to 2025. Drawing on 1,171 Scopus-indexed documents (articles, conference papers, and book chapters), the study employs co-word analysis (keyword co-occurrence), co-authorship analysis, and thematic evolution mapping using VOSviewer and Biblioshiny to examine publication trends, influential contributors, collaboration patterns, and evolving themes. The analysis demonstrates a steady rise in publications, especially after 2020, signaling intensified scholarly attention to science literacy in addressing global challenges such as health crises, climate change, and technological transformation. Keyword networks and thematic evolution further indicate a conceptual shift from treating science literacy mainly as an educational outcome to framing it as a multidimensional construct integrating cognitive, social, digital, and ethical dimensions. The United States, China, and Indonesia emerge as major contributors, alongside expanding international collaboration and diversified research contexts. Core themes scientific literacy, education, and students now connect strongly with emerging topics including health literacy, digital literacy, and citizen science. Overall, these results highlight science literacy's crucial role in supporting inquiry-based learning, informed citizenship, and sustainable development, while also identifying dominant trends, research gaps, and implications for inclusive, evidence-based science education worldwide.

Keywords: Bibliometric Analysis, Digital Literacy, Global Research Trends, Science Education, Scientific Literacy

A. Introduction

The accelerated advancements in science and technology throughout the 21st century have heightened global awareness of the critical role of science literacy in shaping informed citizens, promoting critical engagement, and supporting sustainable development. In an era increasingly characterized by misinformation, disinformation, and the spread of "post-truth" narratives, science literacy serves as an essential tool for individuals to critically evaluate evidence, navigate uncertainty, and make sound

decisions regarding complex societal issues (H. R. Balan et al., 2025a; Devlin et al., 2025; J. Towler, 2025; O. Towler, 2025). Far from being limited to factual knowledge, science literacy encompasses scientific reasoning, inquiry-based learning, problem-solving, communication, and social awareness (Cairns, 2025; Gray, 2025).

International education frameworks have strongly advocated for science literacy integration within curricula. Both the Next Generation Science Standards (NGSS) **and** Sustainable Development Goal 4 (SDG 4) emphasize embedding literacy skills into science education to prepare learners for global competence and lifelong learning (Chiu & Lien, 2025; Podgórska & Zdonek, 2024; Zuñiga-Quispe & Gonzales-Macavilca, 2025). These efforts are mirrored by national strategies, such as Canada's inclusive STEM initiatives (Boechler et al., 2025) and (H. R. Balan et al., 2025b; Kumar & Choudhary, 2025; Zarkasi et al., 2025), which integrate ethical, cultural, and civic perspectives into science learning.

From a theoretical standpoint, science literacy is best understood as the interplay between knowledge, reasoning, and communication. Studies by (S. Minocha et al., 2025; T. Minocha et al., 2025; Nichols et al., 2025; Paletta, 2024) show that disciplinary literacy practices—such as inquiry dialogue, writing, and mentorship—play a critical role in helping learners understand how scientific claims are constructed and validated. Additional research highlights how strong numeracy and analytical reasoning central to science literacy help individuals interpret data and minimize cognitive biases (Buroidah et al., 2024; Perrin et al., 2025). These capacities align with cognitive and epistemic learning theories, where knowledge acquisition is seen as an active, inquiry-driven, and reflective process. Moreover, researchers such as (Ergai et al., 2023; S. Ganesan, 2025; Heikkilä et al., 2025) stress the need for linguistically responsive and culturally inclusive instruction**,** especially for multilingual learners, to support deeper conceptual understanding.

Pedagogical innovations are increasingly employed to link science literacy with improved scientific knowledge acquisition. For instance, (R. Costa et al., 2025; W. F. D. S. Costa et al., 2025; Lodén et al., 2025; Thuan & Son, 2025) found that inquiry-based activities, like temperature mapping in urban settings, can enhance reasoning and investigative skills. Similarly, gamified learning environments have been shown to boost adolescent engagement and knowledge around scientific topics, such as vaccinations (U. Ganesan, 2025; Kantorski et al., 2025; Xiang et al., 2024). Scholars like (Roessger & Greenleaf, 2025; Zuñiga-Quispe & Gonzales-Macavilca, 2025) advocate interdisciplinary approaches merging journalism and biology to develop media literacy and science communication skills. Literacy-oriented assessments are also gaining traction as tools for evaluating students' grasp of climate science (A. Balan et al., 2025; H. R. Balan et al., 2025b; Kresin et al., 2024).

Despite these advances, challenges remain in establishing a direct, measurable relationship between science literacy and scientific knowledge acquisition. While students may express interest in science, studies show that this does not always translate into deep conceptual (H. R. Balan et al., 2025a; Cansiz, 2024). Moreover, research has found gaps in genetics literacy, particularly among secondary students (Maaoui et al., 2025; Maghfiroh et al., 2025; Smit et al., 2025). Factors like gender, socioeconomic status, and ideology also shape disparities in science understanding (G. R. Demétrio et al., 2025; M. Demétrio et al., 2025; Jain et al., 2025; Long & Hock, 2025; Pennycook et al., 2022). A recurring limitation in the current literature is its fragmentation: studies often lack longitudinal design, cross-national comparisons, and fail to integrate multiple forms of literacy such as digital, disciplinary, and media literacy into a cohesive analytical framework (Cairns, 2025; M. Demétrio et al., 2025).

To address these research gaps, this study conducts a comprehensive bibliometric and thematic analysis of global literature on science literacy and its impact on scientific knowledge acquisition**,** covering Scopus-indexed publications from 2016 to 2025. This bibliometric review is guided by six critical research questions:

1. How has the research output on science literacy evolved over time?
2. Which journals are most influential in the field?
3. Who are the leading contributing authors?
4. Which countries are producing the highest volume of research?
5. What are the recurring keywords and research themes?
6. How have thematic structures shifted over the last decade?

B. Methods

This study adopts a bibliometric mapping approach to investigate global research trends concerning science literacy and its impact on scientific knowledge acquisition. Bibliometric analysis enables the systematic examination of extensive academic literature by uncovering publication patterns, citation networks, authorship collaborations, and evolving thematic clusters. The primary goal is to visualize the intellectual and structural development of this field between 2016 and 2025. The study quantifies publication outputs, citation trends, and co-occurring themes to map the scholarly landscape, using metrics such as author productivity, journal influence, and keyword associations.

Data were collected from the Scopus database on October 19, 2025. Scopus was chosen due to its comprehensive indexing of peer-reviewed literature and advanced bibliometric capabilities. The search was conducted using the TITLE-ABS-KEY field with the keywords: “Science Literacy” and “Scientific Knowledge”. The initial query returned 2,124 documents. After applying a set of inclusion and exclusion criteria, 1,171 documents were selected for analysis. To ensure data relevance and rigor, three

inclusion criteria were applied: (1) Publication Year—only documents from 2016–2025 were included, representing a decade of intensified focus on science literacy; (2) Document Type—only peer-reviewed journal articles, conference papers, and book chapters were retained, excluding editorials, letters, and reviews; and (3) Language—only English-language publications were selected, resulting in a final dataset of 1,171 documents. The data were exported in CSV and RIS formats, cleaned through deduplication, normalization, and keyword unification, and analyzed using Microsoft Excel (for descriptive statistics), VOSviewer (for bibliometric mapping), and Biblioshiny (for thematic and collaboration analysis) shown in figure 1.

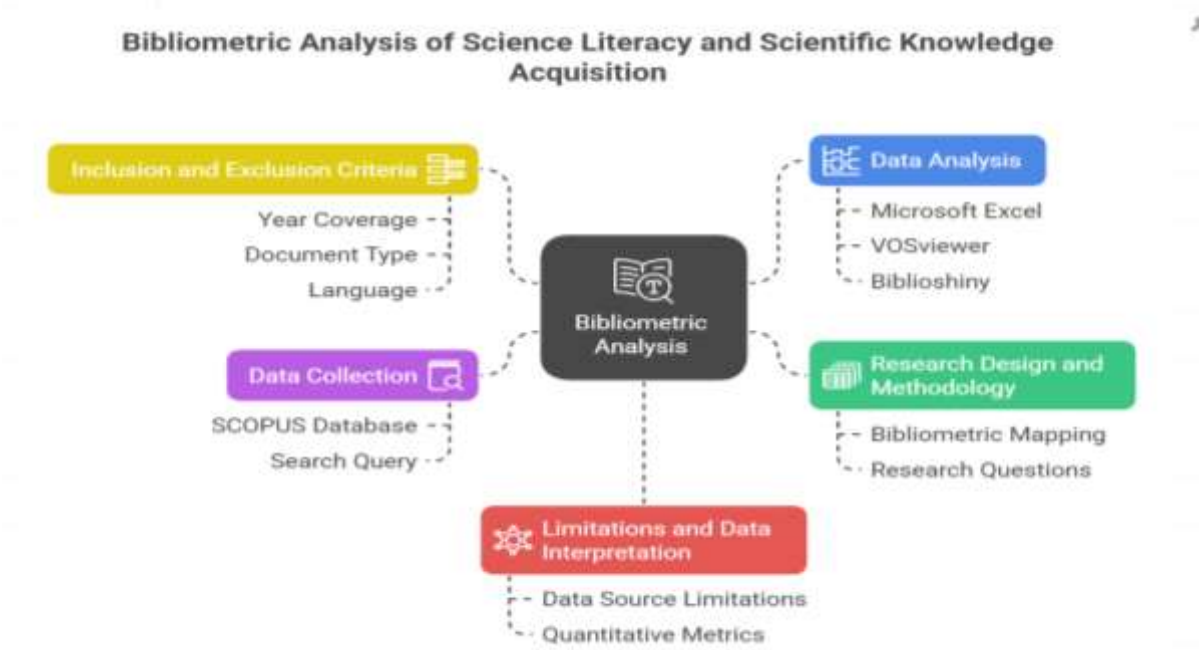

Figure 1 The steps in collecting and analyzing the data

C. Results and Discussion

1. Results

1.1 Publication Trends from 2016 to 2025

Figure 2 illustrates publication trends on science literacy and its relationship to scientific knowledge acquisition based on 1,171 documents retrieved from the Scopus database (https://www.scopus.com) for the period 2016–2025. These documents—which include peer-reviewed journal articles, conference proceedings, and book chapters—show a consistent upward trajectory in publication output. Starting from 73 publications in 2016, the number steadily increased to 159 by 2025. This rising trend underscores the growing scholarly and institutional interest in science literacy as a

response to global educational and societal challenges. The increase coincides with heightened awareness of science-related issues such as climate change, pandemic preparedness, and digital transformation, all of which demand scientifically literate populations. The findings reinforce the recognition of science literacy as a critical competency for informed citizenship and participatory decision-making.

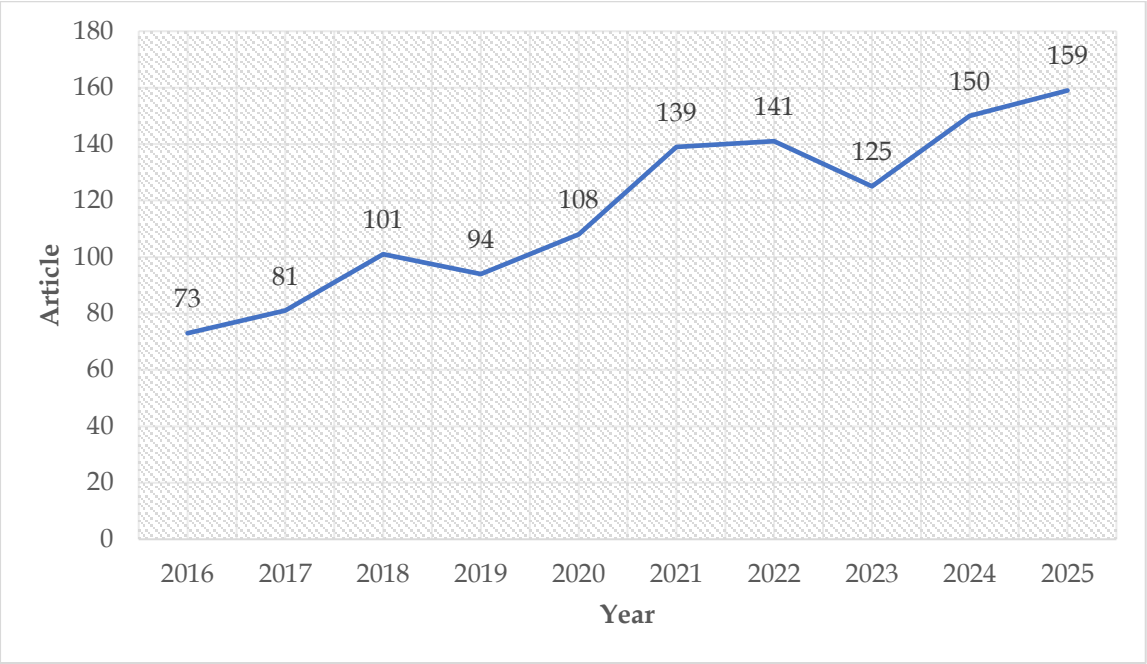

Figure 2. Number of articles published annually from 2016 to 2025

1.2 Most Relevant Sources and Author

The analysis of the most relevant publication sources in the domain of science literacy and its impact on scientific knowledge acquisition between 2016 and 2025 identifies the leading journals and conference proceedings shaping the field. As illustrated in Figure 3, the Journal of Physics: Conference Series ranks highest with 109 contributions, followed by the International Journal of Science Education (52 documents) and the AIP Conference Proceedings (48 documents). Additional influential sources include Science and Education (37 documents), Sustainability (Switzerland) (26 documents), and Research in Science Education (20 documents). These results highlight the central role of both discipline-specific conferences and high-impact journals in disseminating research on science literacy. The presence of sources from physics education and sustainability domains reflects the interdisciplinary scope of the field, encompassing theoretical, empirical, and practice-oriented research. The sustained publication growth in these outlets also signals increasing global scholarly engagement with science literacy as a critical element of science education and public understanding of science.

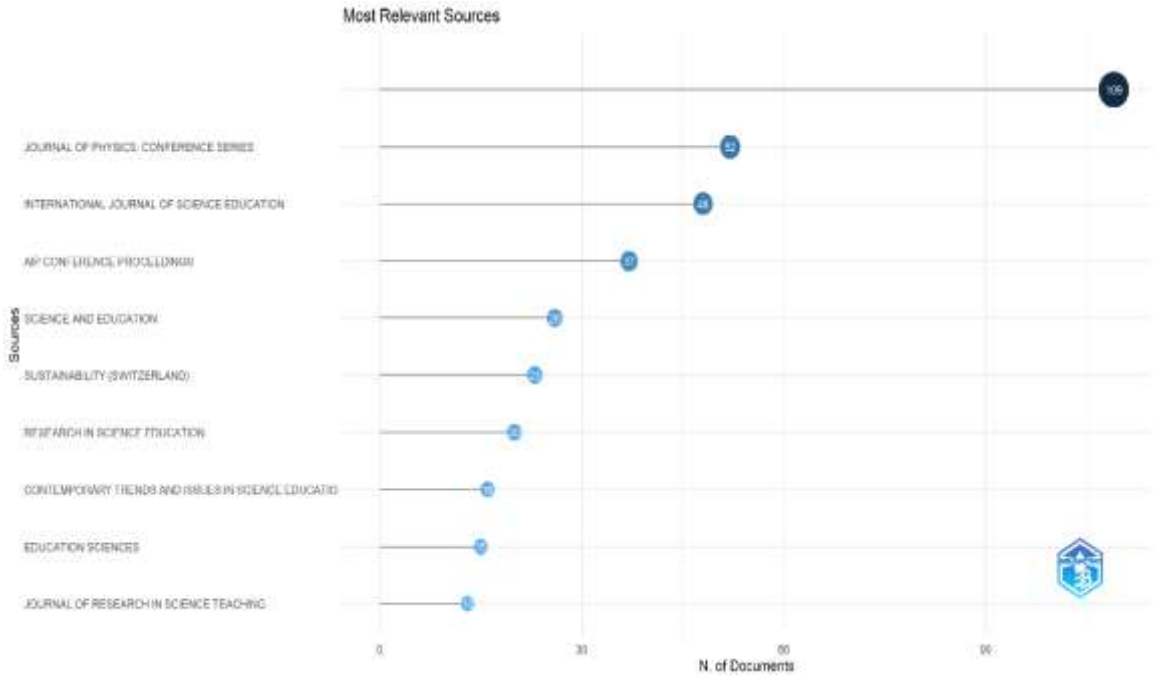

Figure 3. Most relevant sources

The analysis of the most relevant sources in the field of *Science Literacy* and its impact on *Scientific Knowledge Acquisition* from 2016 to 2025, as summarized in Table 1, indicates a diverse range of journals contributing significantly to the literature. The International Journal of Science Education leads in the number of publications with 48 documents and 641 citations, followed by the Journal of Physics: Conference Series with 52 documents and 261 citations, highlighting the prominence of both education-focused and discipline-specific venues. Other key sources include Science and Education (26 documents, 517 citations), Public Understanding of Science (12 documents, 1007 citations), and the Journal of Research in Science Teaching (13 documents, 375 citations), indicating that high-impact journals in science education continue to shape the discourse on science literacy. The presence of journals such as Sustainability (Switzerland) and Jurnal Pendidikan IPA Indonesia reflects an increasing emphasis on integrating science literacy with interdisciplinary and regional educational perspectives.

Table 1. Top 10 most source titles that contribute to the publication

Rank	Relevant sources	Document	Citation
1	Public understanding of science	12	1007
2	International journal of science education	48	641
3	Science and education	26	517
4	Journal of research in science teaching	13	375
5	International journal of science and mathematics education	8	312
6	Science education	13	311
7	Journal of physics;conference series	52	261
8	Sustainability(Switzerland)	23	186
9	Research in science education	20	168
10	Jurnal ipa Pendidikan indonesia	10	166

The country-author-keyword network analysis presented in Figure 4 illustrates the global landscape of research on science literacy and its impact on scientific knowledge acquisition from 2016 to 2025. The United States emerged as the most prolific contributor, followed by Italy, Indonesia, China, and Spain, indicating a concentration of scholarly activity across both Western and Asia-Pacific regions. The network also reveals strong associations between leading authors and frequently occurring keywords such as “scientific literacy,” “education,” “students,” “knowledge,” and “teaching,” suggesting that the literature is thematically anchored in the educational functions of science literacy and its role in supporting conceptual understanding. This network structure highlights the field’s international scope and interdisciplinary integration, showing that research is both geographically dispersed and thematically cohesive. The results reflect a growing global consensus on the importance of science literacy in shaping contemporary education, with scholars from diverse national contexts contributing to theoretical innovation and pedagogical advancement in science teaching and learning.

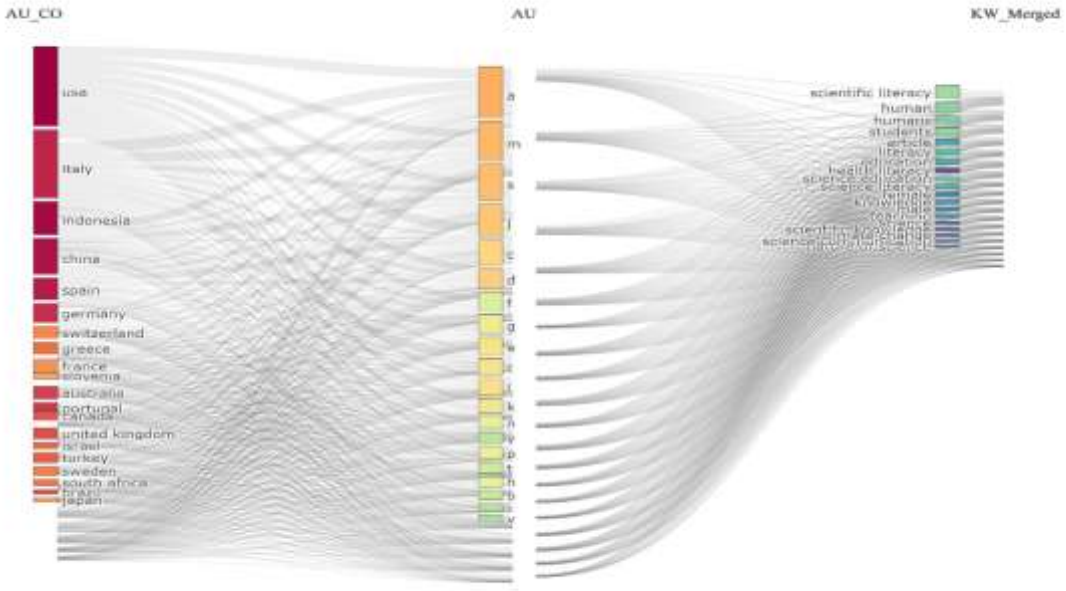

Figure 4. Three field plot of Authors, author country, and affiliation

1.3 Most Influential Countries

The analysis of international research collaborations in the field of science literacy and its impact on scientific knowledge acquisition, as depicted in Figure 5. The United States appears as the most prominent hub within the network, highlighting its central role in fostering cross-national research partnerships. Other major contributors include Germany, the United Kingdom, Indonesia, China, and Spain, reflecting a balanced mix of established and emerging research economies. The co-authorship map displays strong interregional linkages among Europe, North America, and Asia, suggesting a high degree of interdisciplinarity and cross-border cooperation. The growing involvement of countries such as Indonesia, China, and Turkey signals a shift toward broader geographic inclusion and a decentering of Western-dominated scholarly networks. These collaborative patterns emphasize the global acknowledgment of science literacy as a strategic priority in education policy and practice, with international partnerships playing a vital role in shaping inclusive, context-sensitive models of scientific knowledge acquisition.

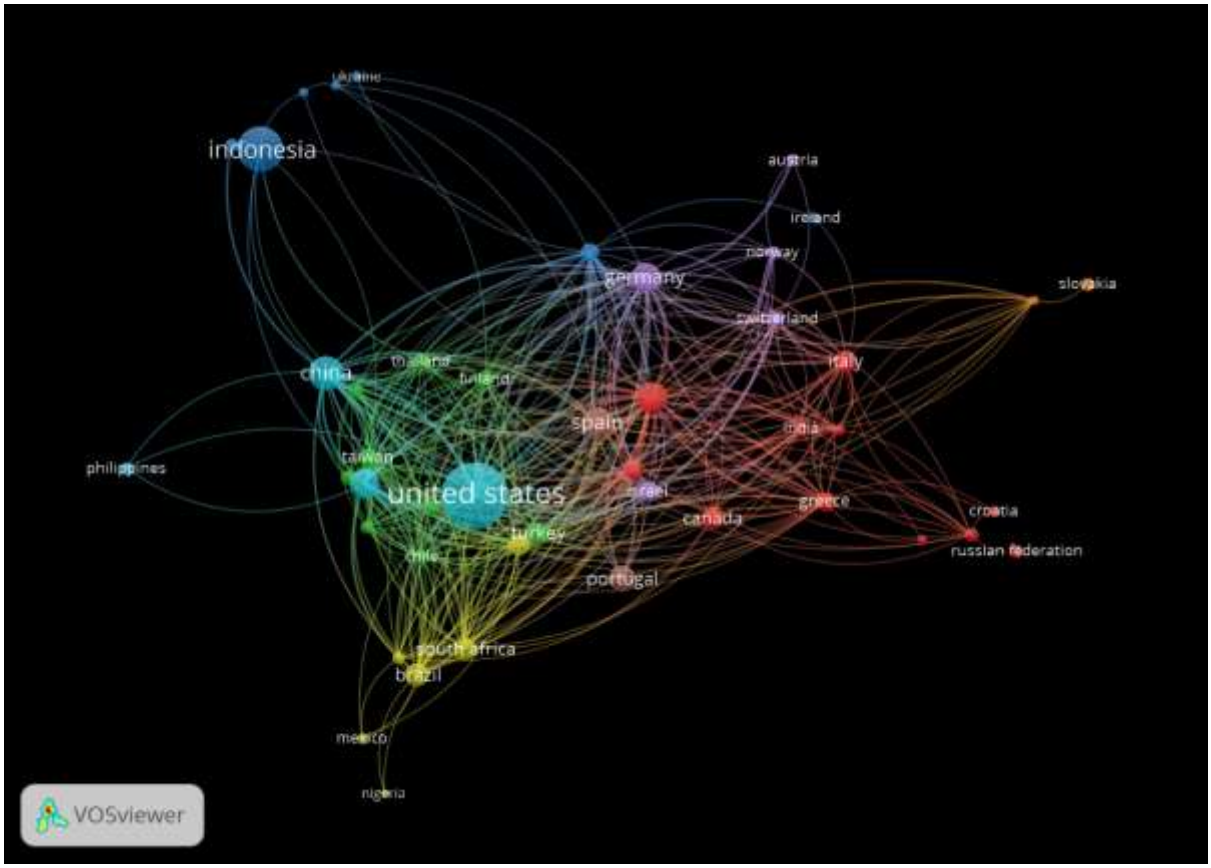

Figure 5. Bibliographic coupling of countries

1.4 Keyword Co-occurrence Analysis

Tree map authors' keyword shown in Figure 6**,** *scientific literacy* (289 occurrences; 12%) remains the dominant keyword, followed by *students*, *human*, *science education*, and *education*, underscoring the field's enduring educational orientation and human-centered focus.The frequent use of terms such as *knowledge*, *teaching*, *curricula*, and *decision-making* indicates a strong emphasis on pedagogical innovation, cognitive development, and epistemic understanding as key components of science literacy. Meanwhile, the emergence of keywords like *climate change*, *health literacy*, *COVID-19*, and *citizen science* reflects a broadening thematic scope, where science literacy is recognized as essential for addressing socio-scientific challenges and guiding evidence-based policy-making. Furthermore, the inclusion of gender-related and methodological terms points to increasing diversity in research populations and approaches**,** highlighting greater inclusivity and methodological pluralism**.**

Figure 6. Tree map of authors' keywords

The bibliometric network visualization generated using VOSviewer (Figure 7). The red cluster focuses on *scientific literacy, students, engineering education,* and *socio-scientific issues*, emphasizing curriculum reform, inquiry-based learning, and STEM integration**.** The green cluster, built around *literacy, knowledge,* and *citizen science*, represents studies on epistemic cognition, public engagement**,** and knowledge construction. The yellow cluster**,** with *health literacy, COVID-19,* and *public understanding of science*, highlights research linking literacy **to** health communication and socio-scientific challenges. The blue cluster, featuring *female, psychology,* and *education research*, integrates gender-sensitive and psychological perspectives. Lastly, the orange cluster—with *teacher education, critical thinking,* and *problem-based learning*—emphasizes teacher development, instructional design, and reflective pedagogy.Collectively, these clusters demonstrate a dynamic, interdisciplinary progression in science literacy research—shifting from traditional educational assessment toward an integrated exploration of societal, behavioral, and cognitive dimensions that shape science education and public understanding.

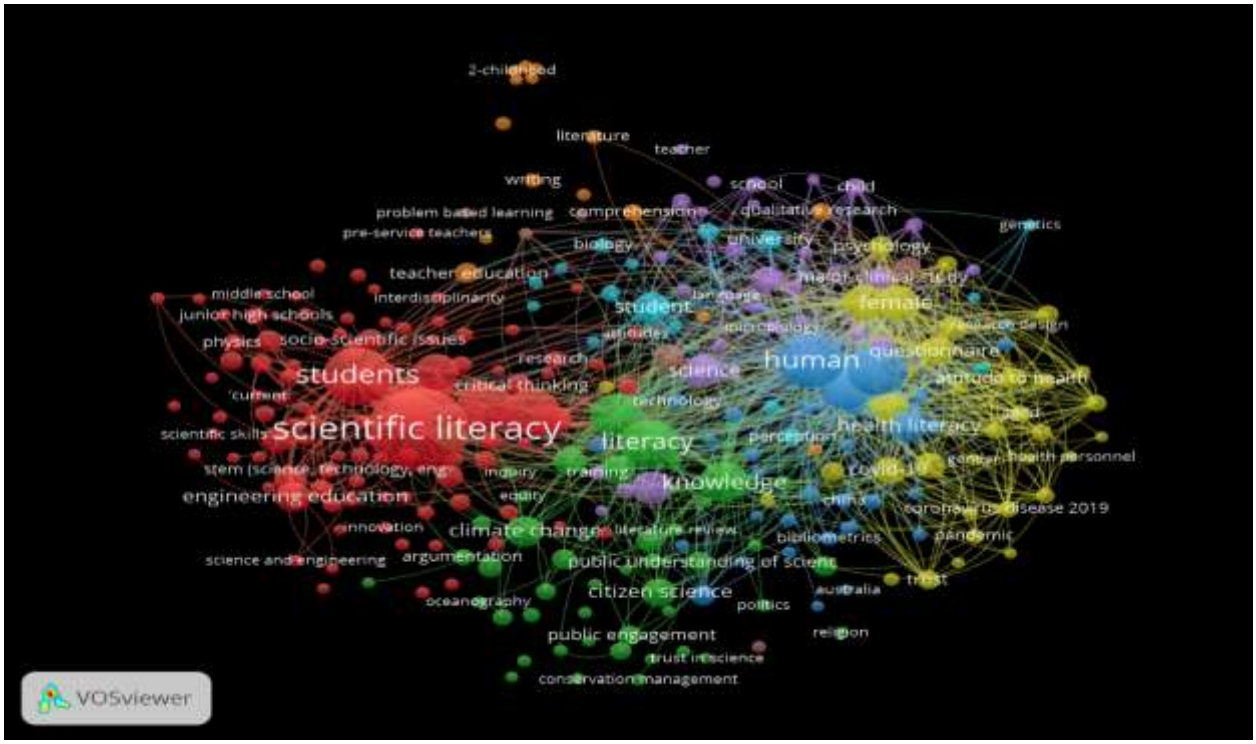

Figure 7. Keywords co-occurrence analysis by network visualization

1.5 The Current Research Landscape

The trend topic visualization (Figure 8) In the early phase (2016–2018), studies focused on foundational themes such as *education, students, literacy, science learning,* and *writing*, emphasizing pedagogical foundations, conceptual understanding, and instructional practices. During the intermediate phase (2019–2021), emerging topics like *scientific reasoning, competence, information dissemination,* and *social media* reflected a shift toward exploring how scientific knowledge is constructed and communicated within digital and public contexts. The 2020–2022 period marked a turning point, driven by global disruptions, with keywords such as *COVID-19, health literacy, psychology,* and *human behavior* highlighting the critical role of science literacy in health communication, behavioral response, and pandemic adaptation.In the latest period (2023–2025), themes such as *artificial intelligence, local wisdom, community participation,* and *ethical reasoning* demonstrate an interdisciplinary expansion integrating technology, culture, and civic engagement. Collectively, these developments illustrate a paradigm shift from traditional educational frameworks toward socially embedded and technologically mediated models, positioning science literacy as both a cognitive skill and a societal asset essential for navigating the complexities of the modern scientific world.

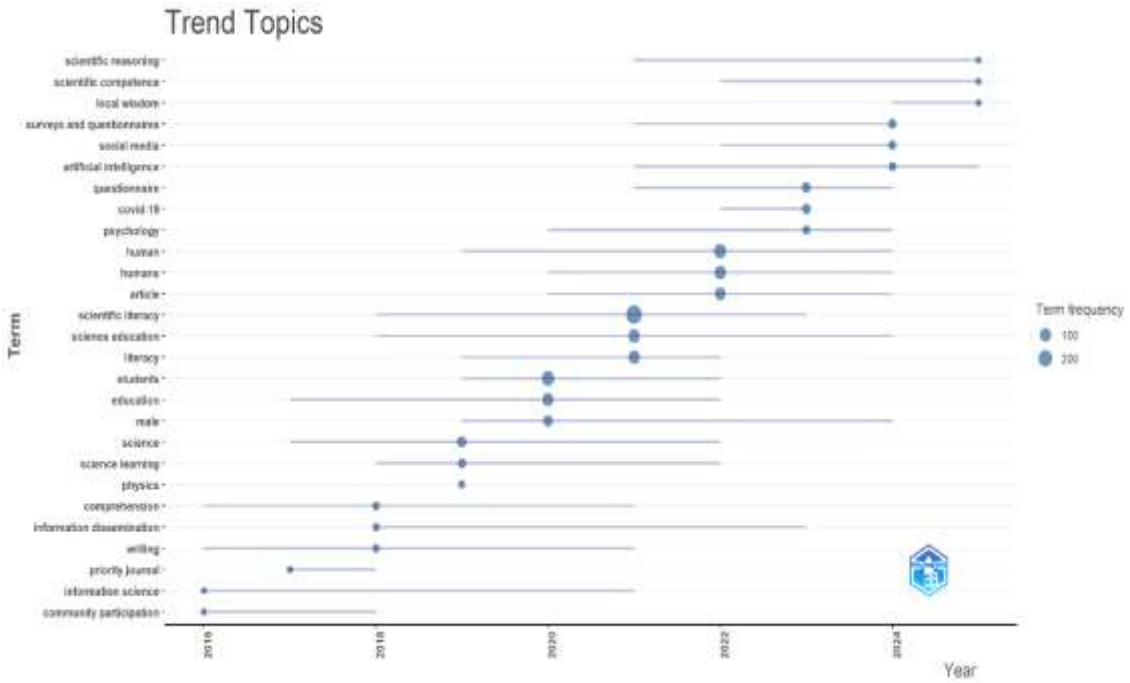

Figure 8. Trend topics of Science Literacy and Its Impact on Scientific Knowledge Acquisition: A Review of Current Research and Practices

The thematic mapping analysis (Figure 9) The Motor Themes (upper-right quadrant) including *scientific literacy, students,* and *science education* serve as the core drivers of the field, linking literacy with conceptual understanding, critical thinking, and academic achievement. Also within this quadrant, terms like *human* and *article* indicate ongoing human-centered inquiry and the global dissemination of scientific research**.** The Basic Themes (lower-right quadrant) featuring *literacy, science literacy,* and *education* represent the foundational constructs that underpin theoretical and empirical work across disciplines.The Niche Themes (upper-left quadrant)—such as *instructional strategies, methods and materials,* and *childhood education*—reflect specialized yet isolated research areas**,** emphasizing pedagogical innovation and early science learning. Meanwhile, the Emerging or Declining Themes (lower-left quadrant) including *teacher education, comprehension, qualitative research,* and *professional development* denote newly evolving or diminishing areas of inquiry. Collectively, the thematic map portrays a maturing and diversified research landscape**,** rooted in educational and humanistic paradigms while expanding into innovative pedagogical and methodological domains, affirming science literacy's vital role in lifelong learning, civic engagement, and interdisciplinary knowledge development**.**

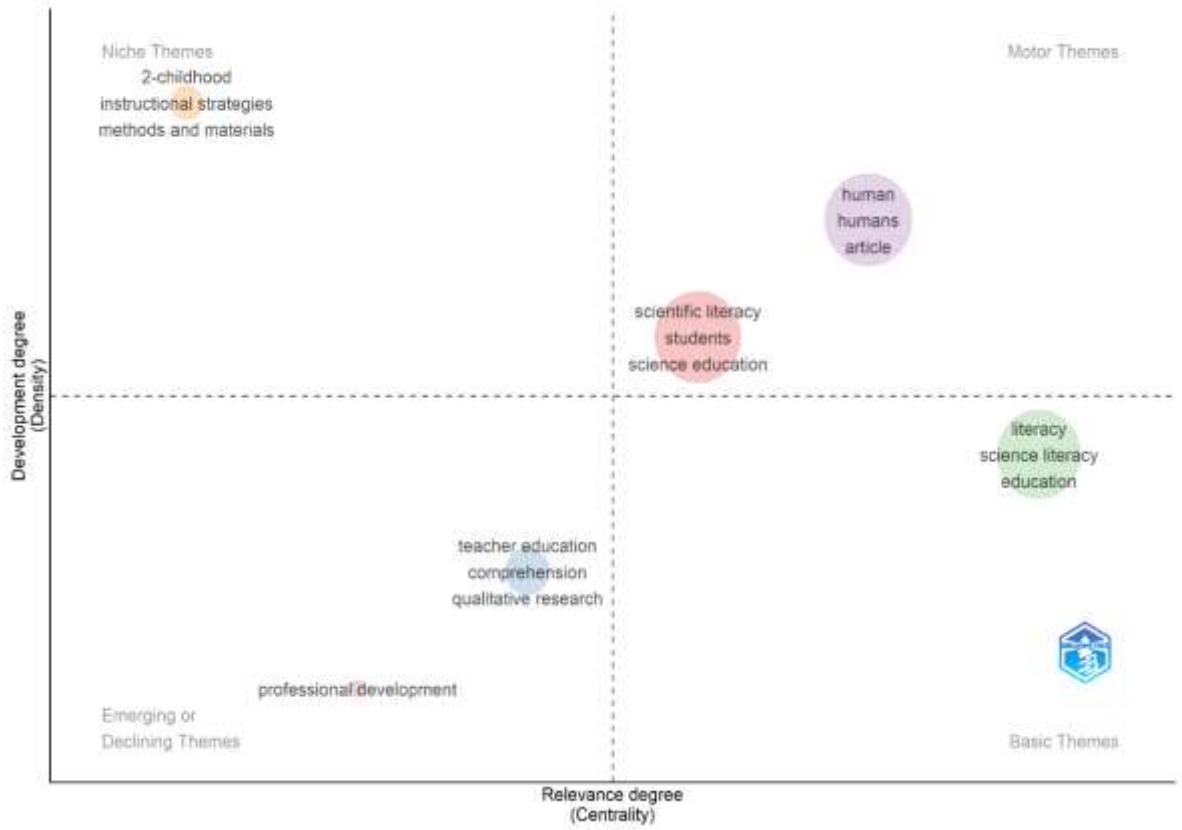

Figure 9. Thematic map of Science Literacy and Its Impact on Scientific Knowledge

The thematic evolution analysis (Figure 10) In the early phase (2016–2019), studies focused on core concepts such as *education, scientific literacy,* and *students*, reflecting foundational efforts to define and measure science literacy within traditional educational contexts. The transitional phase (2020–2021) introduced themes like *environmental education, media literacy, argumentation,* and *qualitative research*, signaling a methodological expansion toward inquiry-based and socio-scientific approaches. The consolidation phase (2022–2024) marked increasing interdisciplinary integration, with the emergence of *digital literacy, project-based learning, science education,* and *human-centered approaches*, emphasizing technology, authentic learning, and learner autonomy in literacy advancement. By 2025, the field evolved into a highly diversified thematic network, incorporating emerging priorities such as *citizen science, climate change, engineering education, health literacy, equity,* and *scientific competence*. This evolution represents a shift from fragmented educational models to a holistic and socially embedded framework, establishing science literacy as a cornerstone for epistemic engagement, civic participation, and lifelong learning within the broader pursuit of global sustainability and scientific empowerment.

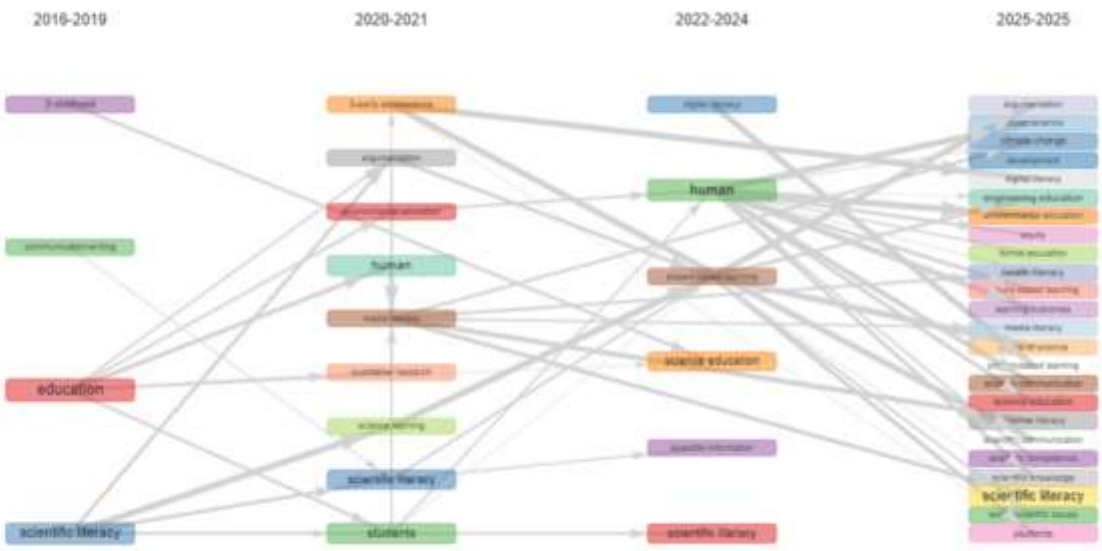

Figure 10. Thematic Evolution of Scientific Argumentation in the Development of STEAM-Based Physics Teaching Materials for Pre-Service Teachers

2. Discussion

The findings of this bibliometric and thematic review provide comprehensive insights into the evolving landscape of research on science literacy and its influence on scientific knowledge acquisition from 2016 to 2025. The analysis of 1,171 Scopus-indexed documents demonstrates a steady increase in research productivity and thematic diversification, confirming that science literacy has become a pivotal concept in contemporary science education. No longer confined to cognitive attainment or factual understanding, science literacy is increasingly framed as a multidimensional construct integrating cognitive, social, digital, and ethical dimensions of learning. The sharp rise in publications after 2020 reflects growing global recognition of science literacy as a foundation for informed citizenship, public resilience, and sustainable development in the face of challenges such as climate change, health crises, and digital transformation

Rather than merely representing topical groupings, the clusters signal shifts in the field's epistemic priorities and social relevance. The red cluster—dominated by socio-scientific issues, STEM, and problem-based themes—has become central because global educational agendas have moved from "learning science" to "using science in society." This cluster's prominence suggests that researchers increasingly treat science

literacy as a competence for navigating contested, real-world problems (e.g., climate policy, emerging technologies, environmental risk). The centrality of socio-scientific issues also indicates a normative turn in the field: science literacy is not only about knowing scientific concepts, but about reasoning with evidence, evaluating claims, and making ethical judgments in civic life. In short, the red cluster is central because it aligns science literacy research with urgent societal demands and positions STEM learning as a vehicle for socio-scientific decision-making.

The emergence of the yellow cluster health literacy, COVID-19, public understanding of science—demonstrates the field's responsiveness to global events. Its rapid growth after 2020 shows that science literacy scholarship can reorient quickly when public welfare depends on scientific comprehension and trust. Conceptually, this cluster highlights that science literacy is not limited to classrooms; it becomes most visible when societies need to interpret uncertainty, evaluate misinformation, and translate scientific evidence into everyday behavior. Methodologically, the yellow cluster also reflects expansion toward public communication, media analysis, and digital information environments areas that became critical during the pandemic. Hence, the yellow cluster represents a "stress test" for science literacy: global crises amplify which aspects of literacy matter most for survival and social coordination.

Over the past decade, the conceptualization of science literacy has undergone a profound transformation. Earlier studies primarily viewed it as a measurable indicator of students' scientific understanding within formal educational contexts. Recent literature, however, increasingly defines it as a broader framework encompassing critical reasoning, epistemic awareness, digital competence, and civic responsibility. Importantly, this shift directly supports the theories highlighted in the introduction. The move toward multidimensional frameworks is consistent with sociocultural learning theory, which emphasizes that knowledge is constructed through social interaction and cultural tools, and with situated learning theory, which frames literacy as participation in authentic practices rather than mere content mastery. In this sense, the bibliometric trend is not just descriptive: it shows theoretical consolidation, where science literacy is treated as a socially embedded practice shaped by community norms, language, technology, and lived experience. The increasing attention to citizen science, equity, and digital reasoning further reinforces the view that literacy develops through participation in meaningful contexts and through engagement with real problems.The thematic mapping and evolution analyses show that research in this field has become increasingly interdisciplinary, merging perspectives from psychology, communication, environmental science, and digital education. Early studies (2016–2019) emphasized foundational educational aspects such as students, learning outcomes, and instructional methods. As the field matured, newer themes—including climate change, artificial intelligence, health literacy, and citizen science—gained prominence. This thematic expansion indicates both methodological broadening and a shift toward context-driven, problem-based

research. For example, interdisciplinary collaborations have connected environmental education with sustainability-oriented literacy, integrated digital reasoning within science education, and mobilized citizen science to broaden public participation in knowledge creation.

Pedagogically, the field has experienced substantial innovation. Research emphasizes inquiry-based learning, project-based instruction, and gamified pedagogies as strategies to strengthen both science literacy and conceptual understanding. These approaches are increasingly supported by digital tools (simulations, virtual labs, and data platforms), which extend learning into interactive and authentic environments. At the same time, teacher education and reflective pedagogy appear as rising focal points, underscoring that teachers are central mediators of epistemic practices, ethical reasoning, and collaborative inquiry. This aligns again with sociocultural and situated perspectives, where educators scaffold participation in scientific practices instead of only transmitting content.

Beyond classrooms, science literacy research has expanded into socio-scientific engagement and public communication. The growth of themes such as health literacy and public understanding of science illustrates a widening interest in how individuals interpret and apply scientific knowledge in daily decision-making. Equity and inclusion also become more visible, especially in work from Indonesia, Brazil, and multilingual regions showing that sociocultural, linguistic, and gender factors shape literacy outcomes. The structural bibliometric patterns further indicate increasing globalization and collaboration: the United States, China, and Indonesia lead in output, while Turkey and Brazil show rapid growth. This diversification suggests that science literacy is no longer a Western-centric agenda; it is being re-interpreted across varied cultural and developmental contexts, which is essential for tackling global educational inequalities.

Despite these contributions, several limitations should nuance the interpretation of findings. First, the high publication output from venues such as the Journal of Physics: Conference Series likely reflects the strong presence of conference proceedings in the dataset. While proceedings are valuable for capturing emerging ideas and regional participation, they do not always carry the same scholarly influence or review rigor as full peer-reviewed journal articles. Therefore, productivity patterns should not be read as a direct proxy for impact without considering document type and citation behavior.

Second, bibliometric analysis is powerful for revealing topics, structures, and collaboration networks, but it does not evaluate the quality, methodological robustness, or substantive conclusions of individual studies. A cluster's prominence signals activity and thematic attention, not necessarily consensus or evidentiary strength. Accordingly, the patterns reported here should be interpreted as a map of

intellectual focus rather than a validation of research outcomes.
Third, because the dataset is limited to Scopus-indexed documents, some regional or non-English scholarship may be underrepresented. Extending future analyses to Web of Science, Dimensions, or regional databases would strengthen coverage and mitigate indexing bias.

D. Conclusions

This bibliometric and thematic review of 1,171 Scopus-indexed publications from 2016 to 2025 demonstrates a significant global evolution in research on science literacy and its impact on scientific knowledge acquisition. The findings indicate that science literacy has shifted from a content-based educational concept to a multidimensional framework encompassing digital, civic, ethical, and epistemic competencies. The analysis also shows rising publication volume, expanding interdisciplinary approaches, and increasingly diverse thematic emphases such as health literacy, climate change, citizen science, and digital reasoning. The United States, China, and Indonesia emerge as major contributors, with collaborative networks growing across continents.

Practical implications are clear and actionable. For curriculum developers, these results suggest the need to redesign science curricula so that science literacy is treated as a core learning trajectory, not an add-on outcome. Concretely, curricula should (1) embed socio-scientific issues (e.g., climate policy, public health, AI ethics) as recurring contexts for concept learning; (2) integrate structured media- and data-literacy tasks, such as evaluating credibility of online scientific claims and interpreting real datasets; and (3) align assessment with multidimensional literacy by measuring not only conceptual knowledge but also argumentation quality, evidence use, and ethical reasoning. For teachers, the findings encourage shifting classroom practice toward inquiry- and project-based sequences in which students generate questions, investigate with digital tools (simulations, virtual labs, citizen-science platforms), and communicate conclusions to authentic audiences. Teachers should also explicitly teach "how science works" (epistemic understanding) for example, by having students compare conflicting claims, track uncertainty, and reflect on how evidence supports or limits conclusions. For policymakers and teacher educators, the study highlights the priority of professional development that equips teachers to facilitate socio-scientific discussion, digital reasoning, and culturally responsive inquiry, especially in multilingual or diverse settings. Policies should support access to digital learning infrastructure and partnerships with community or citizen-science initiatives to extend literacy beyond school.

Future research should move beyond broad calls for longitudinal and comparative work by targeting specific designs. Longitudinal studies are needed to track how particular interventions for example, sustained citizen-science projects, media-literacy

modules, or inquiry-based STEM programs shape students' scientific reasoning, digital evaluation skills, and civic engagement over multiple years. Comparative studies should explicitly examine contrasts between Western and Eastern educational systems, asking how different curricular traditions, cultural values, and assessment regimes cultivate (or constrain) multidimensional science literacy. In addition, qualitative and mixed-method research such as discourse analysis of classroom argumentation, ethnographic studies of citizen-science participation, or learner-trajectory case studies can reveal how science literacy is enacted in real settings and why certain approaches succeed in particular cultural contexts. Expanding bibliometric scope to include Web of Science and Dimensions would further improve global representation and reduce database bias. Overall, this review provides a robust foundation for advancing research, policy, and practice aimed at building scientifically literate citizens capable of informed decision-making in an increasingly complex world.

E. Acknowledgement

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