



MAPPING TRENDS IN PROJECT-BASED LEARNING AND SCIENTIFIC LITERACY: BIBLIOMETRIC INSIGHTS INTO DIGITAL TOOLS IN SCIENCE EDUCATION

Nuraida Nuraida*	Universitas Sebelas Maret, Surakarta Indonesia	aidanur2@student.uns.ac.id
A. Suparmi	Universitas Sebelas Maret, Surakarta Indonesia	soeparmi@staff.uns.ac.id
Widha Sunarno	Universitas Sebelas Maret, Surakarta Indonesia	widhasunarno@staff.uns.ac.id
Sri Mulyani*	Universitas Sebelas Maret, Surakarta Indonesia	srimulyaniuns@staff.uns.ac.id

*Corresponding authors

ABSTRACT

Aim/Purpose	This study aims to map global research trends in Project-Based Learning (PjBL) and scientific literacy within digitally mediated science education, providing bibliometric insights into the development of themes, methodological patterns, and emerging digital tools.
Background	The acceleration of digital transformation has fundamentally reshaped science education, demanding a redefinition of scientific literacy beyond content mastery toward the integration of digital competencies, critical thinking, and socioscientific reasoning. In digitally mediated environments, learners must navigate vast information ecosystems, distinguish scientific evidence from misinformation, and engage with global sustainability challenges such as climate change. Although Project-Based Learning (PjBL) is widely recognized as an effective constructivist approach for fostering inquiry and real-world problem solving, limited bibliometric evidence comprehensively maps how digital tools and PjBL collectively contribute to scientific literacy development.
Methodology	A systematic literature review guided by the PRISMA framework was conducted using Scopus-indexed publications (2019–2024). Bibliometric techniques, including keyword co-occurrence and co-citation analysis using

Accepting Editor Tharrenos Bratitsis | Received: August 25, 2025 | Revised: January 6, February 15, March 20, April 24, May 12, 2026 | Accepted: May 19, 2026.

Cite as: Nuraida, N., Suparmi, A., Sunarno, W., & Mulyani, S. (2026). Mapping trends in project-based learning and scientific literacy: Bibliometric insights into digital tools in science education. *Journal of Information Technology Education: Innovations in Practice*, 25, Article 23. <https://doi.org/10.28945/5787>

(CC BY-NC 4.0) This article is licensed to you under a [Creative Commons Attribution-NonCommercial 4.0 International License](https://creativecommons.org/licenses/by-nc/4.0/). When you copy and redistribute this paper in full or in part, you need to provide proper attribution to it to ensure that others can later locate this work (and to ensure that others do not accuse you of plagiarism). You may (and we encourage you to) adapt, remix, transform, and build upon the material for any non-commercial purposes. This license does not permit you to use this material for commercial purposes.

	VOSviewer, were applied to 141 screened records to identify thematic clusters, publication trends, and research networks.
Contribution	This study provides a comprehensive bibliometric landscape that clarifies the intersection between digital competencies and PjBL in advancing multidimensional scientific literacy. It bridges fragmented discussions by integrating thematic, methodological, and impact-based analyses.
Findings	Results indicate a steady increase in publications linking “scientific literacy” and “digital literacy,” with PjBL emerging as a dominant pedagogical strategy. Frequently identified digital tools include digital assessment games, virtual learning environments, digital comics, simulations, and data-driven inquiry platforms. Thematic clusters highlight sustainability, socioscientific issues, climate change, citizenship, critical thinking, and misinformation as central concerns. Digital integration positively influences cognitive outcomes (conceptual understanding, inquiry skills, problem-solving) and affective dimensions (motivation and attitudes toward science). However, key challenges include teacher digital competence gaps, fragmented curriculum integration, sustainability alignment complexity, and insufficient assessment frameworks for higher-order inquiry skills.
Recommendations for Practitioners	Educators should integrate sustainability-oriented inquiry, digital simulations, collaborative platforms, and structured project-based models within coherent curricular frameworks. Strengthening teacher professional development in digital pedagogy and digital-scientific assessment is essential.
Recommendations for Researchers	Future studies should prioritize experimental and comparative designs to evaluate specific digital tools, develop integrated assessment frameworks for scientific and digital literacy, and expand design-based research across diverse contexts. Greater attention to artificial intelligence integration and digital equity is also recommended.
Impact on Society	Strengthening digital scientific literacy supports the formation of informed, responsible citizens capable of addressing misinformation, engaging in climate discourse, and making evidence-based decisions in technology-driven societies.
Future Research	Longitudinal studies examining sustained impacts of digitally integrated PjBL, AI-supported inquiry models, and cross-cultural comparative analyses are needed to strengthen evidence-based science education reform.
Keywords	scientific literacy, project-based learning, digital literacy, bibliometric analysis, digital tools, sustainability education, science education, inquiry-based learning, socioscientific issues

INTRODUCTION

The modern digital era has fundamentally transformed the landscape of science education, where scientific literacy now plays a crucial role in enabling individuals to navigate technological complexities and make evidence-based decisions (Giri & Paily, 2020; Gultepe & Kilic, 2015). This digital transformation demands a redefinition of scientific literacy that is no longer limited to mastery of traditional scientific knowledge, but extends to encompass the integration of digital competencies, critical thinking, and problem-solving abilities that empower learners to carefully evaluate scientific information and engage effectively with technology-driven issues (Hobbs & Tuzel, 2017; Thelma et al., 2024).

Digital transformation has changed how learners and the general public access scientific information. This technology can also enhance science learning through broader resources and interactive learning

(Vuorikari et al., 2022). However, scientific literacy in the digital era also presents new challenges, such as the ability to navigate information between scientific and pseudoscientific data online. Digital technologies, such as online learning platforms and interactive simulations, can be effective tools for actively and contextually teaching scientific literacy (Turiman et al., 2012). Social media and online collaborative tools can provide access to global scientific knowledge and support student collaboration in discussing scientific concepts (Fortus et al., 2022).

Although digital technology offers potential for science learning, challenges to scientific literacy in the digital era include assessing the validity of online scientific information and gaps in technology access that can affect digital scientific literacy (Varas et al., 2023). Bibliometric approaches have been used to analyze research trends in scientific literacy in the digital era, providing insights into research developments and future directions (Donthu et al., 2021). Further research is expected to highlight important aspects of digital scientific literacy to support the development of relevant educational policies.

The internationally developed digital competence framework, specifically the European Commission's Digital Competence Framework for Citizens, identifies five main areas of digital literacy competence: information and data literacy, communication and collaboration, digital content creation, safety, and problem-solving (Vuorikari et al., 2022). This framework has been widely cited and used in various international studies as a reference for developing digital competencies (Farias-Gaytan et al., 2023). Recent research shows that digital competence consists of three interrelated dimensions: the technical dimension encompassing visual literacy, problem-solving, and technological understanding; the cognitive dimension, including the ability to read, select, interpret, and evaluate data while considering the appropriateness and consistency of information; and the ethical dimension emphasizing ethical and environmental responsibility in using digital technology (BPIKA, 2024; Falloon, 2020).

Project-Based Learning (PjBL) has emerged as a promising pedagogical approach in education, with research showing an 80% increase in publications since 2014 (de Andrade Gomes et al., 2024). PjBL engages learners in an in-depth investigation of complex real-world problems, where they use various resources and engage in sustained inquiry-based learning activities to produce complete project work and solve interrelated problems within a given time period (L. Zhang & Ma, 2023). The PjBL approach aligns with constructivist ideas proposed by John Dewey, who believed that learning is a natural process that occurs through interaction and reflection on idea-experiences among learners (Hoesny et al., 2024).

The PjBL approach actively engages learners, enhances their understanding of scientific concepts, encourages critical thinking, promotes effective collaborative learning, and ultimately increases their engagement in learning by anchoring it to real-world contexts through learner-centered projects (Ibrahim, 2025). A recent meta-analysis of 66 experimental or quasi-experimental studies over the past 20 years demonstrates that PjBL can effectively enhance learning outcomes with large effect sizes (L. Zhang & Ma, 2023). This study found that PjBL not only improves academic achievement but also develops higher-order thinking skills and essential 21st-century skills.

Research findings reveal that PjBL significantly enhances key 21st-century skills, including problem-solving, teamwork, communication, and creativity, as well as increased learner engagement and motivation (Rehman et al., 2024). Bibliometric research on 36 articles published between 2020 and 2024 proves that PjBL is highly effective in developing scientific literacy and 21st-century skills in science learning. This model encourages learners to engage in real-world inquiry, which significantly enhances their ability to understand and apply scientific concepts (Arifin et al., 2025).

The rapid development of digital technology has fundamentally transformed the science education paradigm in recent years. Educators are now re-evaluating their various teaching methods to cultivate comprehensive scientific literacy in learners. The integration of digital devices in learning contexts provides learners with broader access to meaningful learning experiences (Kaldaras et al., 2024).

Teachers can design digital tools that consider specific learner needs to expand learners' opportunities to acquire scientific knowledge. The foundation of scientific literacy through PjBL becomes an important cornerstone in this educational transformation (Lembens & Krebs, 2025; Silva et al., 2024).

Recent research has explored the advantages and limitations of digital learning in science education, including the use of digital simulations, online resources, collaborative learning, personalized learning, and gamification (Lee et al., 2020). These studies provide evidence that digital learning can significantly improve student engagement, motivation, and learning outcomes, although some researchers have expressed concerns about the technology's potential to replace traditional teaching methods and reduce social interaction (Melgaard et al., 2021). In this regard, digital learning tools effectively meet the diverse needs of learners, facilitate access to personalized feedback, and thus foster the development of self-regulation skills essential for academic success (Maier & Klotz, 2022; Mendoza & Wagner, 2025; Stalmach et al., 2024).

Furthermore, a bibliometric analysis of the Scopus database for the period 2019–2023 revealed a significant increase in publications integrating digital technologies in science education. Technologies such as augmented reality (AR), virtual reality (VR), and blended learning environments have transformed learning to be more interactive, personal, and accessible (Arifin et al., 2025). Bibliometric analyses of 1,338 publications over ten years document accelerated growth in AI-related science education research after 2019, with robotics, chatbots, and machine learning frequently applied to inquiry-based, project-based, blended, and cooperative pedagogy, with results related to greater engagement, scientific literacy, and inquiry skills (Jia et al., 2024; Kavitha & Joshith, 2024).

Bibliometric research on artificial intelligence literacy shows an exponential growth trend in publications, indicating increased academic interest and influence in this field, with an average of 15.04 citations per document (Dalky et al., 2025). These findings confirm that digital literacy, including AI literacy as an emerging construct, has become a major focus in contemporary educational research.

Although scientific literacy in the digital era and PjBL are recognized as having strategic importance, further clarity is still needed regarding the integration of digital skills into current PjBL science education programs (Mardiana, 2024; Turiman et al., 2012). Traditional curricula often prioritize the delivery of content knowledge while neglecting opportunities to incorporate digital devices that can deepen learners' understanding of scientific concepts. Furthermore, many educators lack the training to seamlessly integrate digital literacy into their PjBL practices, thereby posing significant challenges to holistically nurturing learners' scientific literacy (Korneeva et al., 2022). The persistence of the digital divide exacerbates these challenges, educators' resistance, and the need for ongoing professional development (Arifin et al., 2025).

Although several PjBL-related studies have used systematic reviews and bibliometrics, none have combined PRISMA, bibliometrics, and network analysis to conduct a comprehensive assessment of global publications on PjBL (de Andrade Gomes et al., 2024). Existing research has largely focused on knowledge acquisition, inquiry-based learning, and critical thinking in conventional science education paradigms, with limited exploration of how PjBL, when integrated with digital tools, contributes to scientific literacy in contemporary educational environments. Furthermore, although individual digital devices have been studied for their efficacy, there is a scarcity of bibliometric analyses offering a comprehensive overview of trends, impacts, and thematic developments in the integration of project-based learning with digital tools to enhance scientific literacy, particularly in the digital realm (Bidarra & Rusman, 2017; Hobbs & Tuzel, 2017). This gap becomes increasingly crucial given the rapid evolution of digital technology and its impact on project-based science pedagogy.

This study addresses these gaps by conducting a bibliometric analysis of recent research on project-based learning and scientific literacy in the context of the digital era. This research aims to describe

emerging themes, highlight prevalent digital tools and methodologies associated with PjBL and scientific literacy, evaluate research collaboration patterns and thematic evaluation, and explain the relationship between digital competencies, project-based learning, and scientific literacy by examining trends and impacts across various studies. This holistic examination aims to equip educators and policymakers with insights into the current landscape of PjBL integration with digital tools for scientific literacy, enabling them to adopt more effective and evidence-based teaching strategies (Costas et al., 2015; González-Zamar et al., 2020).

The impetus for this research stems from the urgent need to foster a generation capable of making informed decisions in an interconnected, technology-driven world. With educational reforms focused on 21st-century skills, many scholars have explored PjBL but have yet to reach consensus on its effectiveness in enhancing learning (L. Zhang & Ma, 2023). As technology continues to shape industries and public discourse on scientific issues, the development of digital scientific literacy through the PjBL approach becomes an imperative that cannot be delayed (Thelma et al., 2024; Tran et al., 2020).

The main objective of this research is to conduct a bibliometric analysis to understand trends and impacts in scientific literacy research through digital environments. Specific objectives include: (1) identifying key themes, trends, and important digital devices in current scientific literacy literature; (2) evaluating the influence of digital integration on learners' scientific literacy outcomes; and (3) providing recommendations for educators and policymakers on effectively implementing digital skills to enhance scientific literacy in the context of 21st-century learning.

This study is important because it provides a comprehensive overview of project-based learning trends and scientific literacy in the digital era, addressing crucial gaps in the existing literature. By highlighting current themes and global collaboration patterns, and by recommending effective strategies, this research promotes an integrated approach to scientific literacy that combines content knowledge with digital competencies through the PjBL approach. The insights gained offer valuable guidance for curriculum developers, educators, and policymakers in designing educational initiatives that better prepare learners to face the challenges of the digital era (Arifin et al., 2025). Additionally, the bibliometric methodology used in this study facilitates a broader understanding of research patterns, international collaboration networks, and thematic trends that guide future inquiry and improve project-based science education through the integration of digital tools.

BACKGROUND

DIMENSIONS AND FRAMEWORK OF CONTEMPORARY SCIENTIFIC LITERACY

Scientific literacy encompasses understanding scientific concepts and their application in daily life, along with critical thinking and problem-solving abilities (OECD, 2019). In the digital era, scientific literacy has become increasingly important alongside rapid technological development and ease of access to information through the internet. Chu et al. (2016) emphasize that scientific literacy not only encompasses understanding scientific concepts but also evaluating scientific information and distinguishing valid information from misleading information, especially in information-rich digital environments.

To comprehensively understand scientific literacy, it is essential to review the key dimensions that constitute it. Figure 1 presents several important dimensions of scientific literacy relevant in the educational context. First, scientific literacy includes understanding the nature of scientific knowledge, including awareness of the processes of development, testing, and modification of science over time (Norambuena-Meléndez et al., 2023). Second, scientific literacy involves the use of scientific methods in problem-solving and decision-making, skills that are critically important in facing everyday environmental and technological challenges (Gizaw & Sota, 2023). In the educational context, this ability helps students build a deep understanding of the universe through observation, experimentation, and

data analysis. Moreover, scientific literacy also encompasses the development of skills related to science and technology (S&T), such as the ability to analyze critically and creatively, which are needed to interact effectively in today's technology-based society (Korneeva et al., 2022).

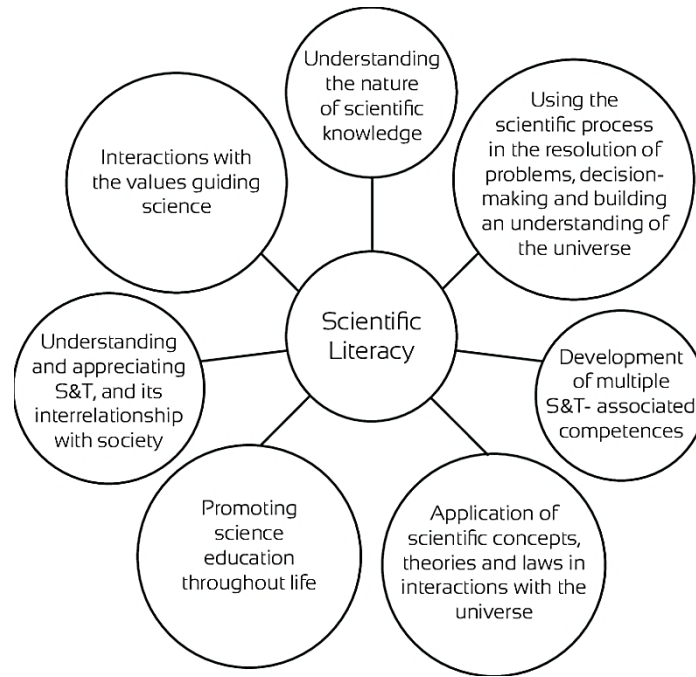


Figure 1. Dimensions of scientific literacy, adapted from Hurd (1998)

Another important aspect of scientific literacy is the application of scientific concepts, theories, and laws in interactions with the universe. This helps strengthen learners' understanding of the interconnections between scientific theory and its application in real situations (Anuar, 2025). Furthermore, it is also important to interact with the values that guide science, where students are expected to develop an understanding of ethics and integrity in scientific practice (Vasquez & Atwood, 2023). This approach helps learners build attitudes that reflect responsible and ethical scientific practice. Understanding the relationship between science, technology, and society is also an important aspect that needs to be developed, so that learners not only appreciate the contributions of science and technology but also understand their implications for society, including in the context of socioscientific issues which demonstrate that the integration of digital skills in science education not only enhances scientific literacy but also forms a deeper understanding of the social implications of scientific progress and technological applications (Bossér, 2024; Litina & Rubene, 2024).

Moreover, promoting lifelong science education is essential, as scientific literacy is not limited to the school environment but is a skill that must be enhanced throughout life (Safrizal et al., 2022). With these dimensions, scientific literacy is expected to help individuals participate effectively in a society increasingly dependent on science and technology. The development of scientific literacy in secondary education is crucial because at this stage, learners begin to form a critical understanding of the world, preparing them to become knowledgeable and responsible citizens.

In the context of this science education transformation, digital literacy becomes a fundamental competency that learners must master to implement the dimensions of scientific literacy previously explained. Digital literacy is defined as the ability to access, manage, understand, integrate, communicate, evaluate, and create information safely and appropriately through digital devices and network technologies to participate in economic and social life (UNESCO Institute for Statistics, 2025). This concept has evolved beyond merely technical skills in operating digital devices to encompass

competencies variously referred to as computer literacy, ICT literacy, information literacy, and media literacy (Farias-Gaytan et al., 2023; UNESCO & Institute for Statistics (UIS), 2025). Given the complexity of higher education institutions, digital literacy requires higher-level competencies, such as reasoning about complexity, which are essential for the development of critical, systemic, scientific, and innovative thinking (Farias-Gaytan et al., 2023).

METHODOLOGY

This section outlines the methodological approach employed to address the research questions. The study adopts a bibliographic literature review approach guided by the PRISMA framework to ensure transparency and replicability. The methodology is organized into several stages: formulation of research questions, data collection, screening, coding, quality appraisal, synthesis, and interpretation of findings.

RESEARCH QUESTIONS

Therefore, this article aims to conduct a bibliometric analysis of research on scientific literacy in science education for the digital era from 2015 to 2024. In doing so, it is hoped that this article will provide a comprehensive overview of the development of this research and its implications for science teaching and guide future research directions. Five research questions were formulated to guide this study, as presented in Table 1.

Table 1. Research questions of the study

RQ	Research question	Description
RQ1	What are the primary themes and trends in scientific literacy research within the context of the digital era?	Examines dominant research themes and emerging trends linking scientific and digital literacy in science education.
RQ2	What digital tools and methodologies are commonly used to develop scientific literacy in modern science education?	Identifies instructional tools and pedagogical approaches employed to enhance scientific literacy through digital integration.
RQ3	What are the impacts of digital literacy integration on students' scientific literacy outcomes?	Analyses reported effects on students' scientific literacy, including critical thinking and problem-solving skills.
RQ4	What challenges do educators face in integrating scientific and digital literacy in science education?	Explores pedagogical, technical, and contextual challenges encountered by educators.
RQ5	What are the future directions and recommendations for enhancing scientific literacy through digital tools in science education?	Synthesizes future research agendas and policy recommendations in the field.

DATA COLLECTION

A systematic literature review is a research approach used to identify, evaluate, and synthesise relevant studies related to specific research questions within a defined topic or phenomenon (Veginadu et al., 2022). In this study, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework was used to ensure transparency, rigour, and replicability in the selection and screening of studies (Selcuk, 2019). To structure the review process, the methodological stages proposed by Lame (2019) were adopted. As recommended, the research questions (RQs) are presented in this Methodology section, as they directly guided the data identification, screening, and analysis procedures.

(1) Formulate research questions (RQs) and conceptual framework

The first stage involved the formulation of clear research questions that defined the scope and analytical focus of the review. The RQs were designed to capture key themes, methodological approaches, impacts, challenges, and future directions of scientific literacy research in the digital era. These questions also served as the foundation for developing the conceptual structure of the review, particularly in relation to digital tools, pedagogical strategies, educational outcomes, and implementation challenges in science education. Based on this focus, five research questions were formulated, as presented in Table 1.

(2) Search and screen for inclusion with eligible criteria

A systematic search was conducted in the Scopus database to identify relevant peer-reviewed journal articles addressing scientific literacy in the context of the digital era. Scopus was selected due to its extensive coverage of high-quality international journals and its compatibility with bibliometric analysis tools. The search strategy employed predefined keywords combined with Boolean operators, including “scientific literacy”, “science education”, and “digital literacy”, applied to the TITLE-ABS-KEY fields.

The inclusion criteria comprised: (a) peer-reviewed journal articles, (b) studies focusing on scientific literacy and digital literacy within science education contexts, (c) publications published between 2019 and 2024, and (d) articles written in English and available in open-access form. The exclusion criteria included: (a) non-English publications, (b) conference papers and non-journal publications, (c) studies conducted outside science or digital education contexts, and (d) articles lacking empirical or analytical relevance to the research questions. The initial search yielded 141 records. These records were screened based on titles and abstracts to assess their relevance to the research questions. The detailed search criteria and screening process are summarised in Table 2.

Table 2. Search strategy and eligibility criteria

Aspect	Description
Timeframe	2019-2024
Databases	Scopus
Searching strings	TITLE-ABS-KEY (“scientific literacy” AND “science education”)
Inclusion criteria	Peer-reviewed journal articles; focus on scientific and digital literacy in science education; English; open access
Exclusion criteria	Non-English publications; conference papers; studies outside science or digital education; articles without empirical or analytical relevance
Total record	141

(3) Coding and conceptual mapping

Each study selected for full-text review was systematically coded using a predefined conceptual framework. The coding categories included themes such as *digital tools in science education*, *instructional and pedagogical methodologies*, *learning outcomes related to scientific literacy*, and *challenges faced by educators*. This coding process enabled structured comparison across studies and facilitated thematic synthesis aligned with the research questions.

(4) Quality appraisal

A quality appraisal process was applied to ensure the inclusion of methodologically sound and relevant studies. Each article was evaluated based on: (a) methodological rigour, (b) relevance to the research questions, and (c) clarity and credibility of reported findings. Studies that did not meet these criteria or lacked a clear connection to the study’s conceptual focus were excluded from further analysis.

(5) Synthesis of the selected studies

The coded studies were synthesised to identify key patterns, themes, and research trends in scientific literacy within the digital era. The synthesis was guided by the research questions and organised around major thematic categories. In addition to thematic synthesis, bibliometric indicators such as publication trends and citation frequencies were analysed to provide insights into the development and impact of research in this field over time.

(6) Interpret and communicate the findings

The findings were interpreted in relation to the research questions to generate an integrated understanding of how scientific literacy and digital competencies are addressed in contemporary science education. The synthesis highlights key challenges, pedagogical opportunities, and future research directions relevant to educators, researchers, and policymakers. The overall review process and study selection stages are illustrated through a PRISMA flow diagram, presented in Figure 2.

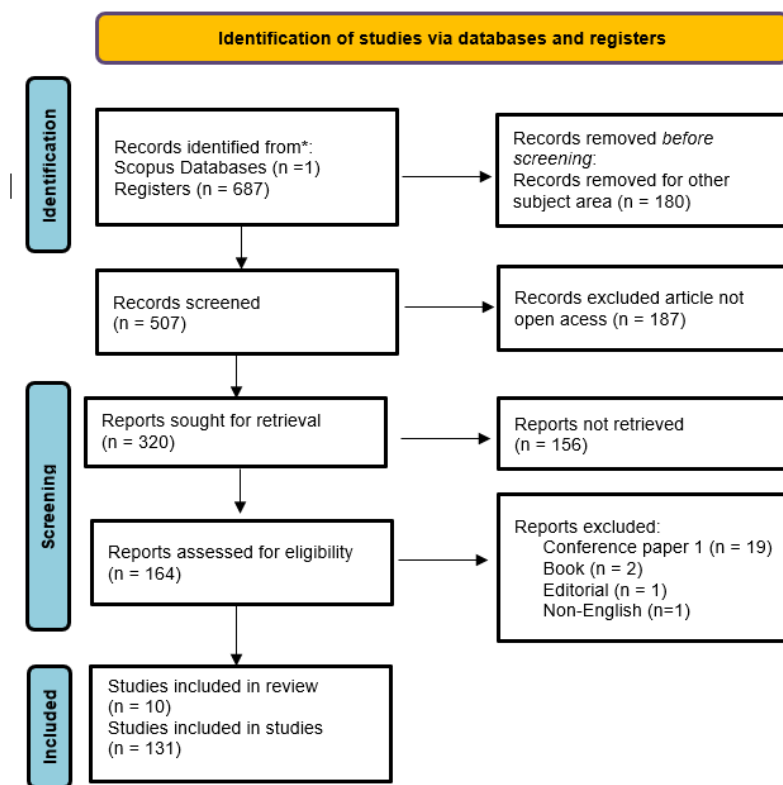


Figure 2. PRISMA flow diagram of the bibliographic literature review process
(Page et al. (2021), used with permission)

RESULTS

This section presents the results of the bibliographic analysis organised according to the research questions (RQs). The findings include publication and citation trends, thematic structures identified through keyword co-occurrence analysis, and methodological patterns related to digital tools and scientific literacy in science education.

RQ1: WHAT ARE THE PRIMARY THEMES AND TRENDS IN SCIENTIFIC LITERACY RESEARCH WITHIN THE CONTEXT OF THE DIGITAL ERA?

Figure 3 illustrates the annual distribution of publications and citations related to scientific literacy research from 2019 to 2024. The results indicate a general upward trend in publication output, reflecting growing academic interest in scientific literacy within the digital era. The number of publications increased steadily from 11 articles in 2019 to a peak of 27 articles in 2022, before stabilising at approximately 25 publications per year in 2023 and 2024. In contrast, the total number of citations shows a declining pattern after 2021.

While citation counts peaked in 2020, a noticeable decrease was observed in subsequent years. This pattern should be interpreted with caution, as newer publications typically take time to accumulate citations, and citation counts in recent years often reflect references to earlier foundational studies rather than to more recent works. Therefore, the observed decline is likely attributable to the temporal dynamics of citation accrual rather than a reduced scholarly impact of recent research.

Overall, the results suggest that scientific literacy research in the digital era is an expanding field, with increasing publication activity, while citation patterns reflect expected delays in citation accumulation for newer studies.

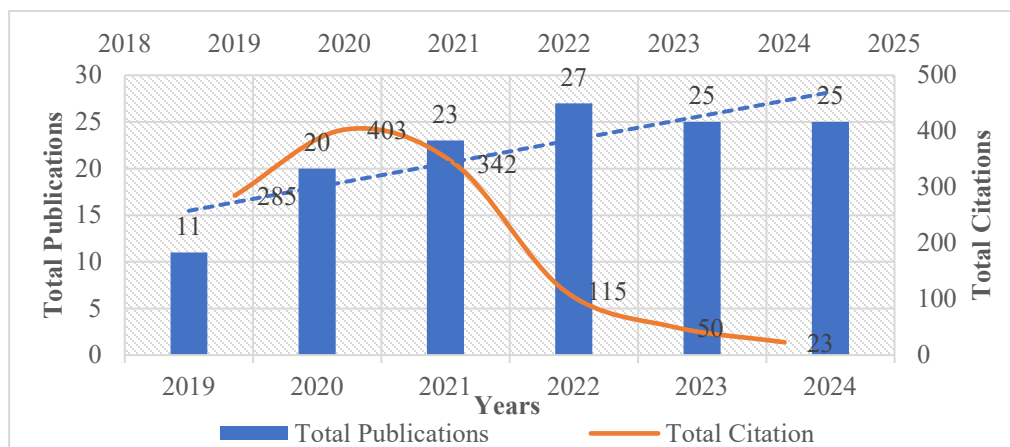


Figure 3. The year-based trend of included publications and citations

To explore thematic structures, keyword co-occurrence analysis was conducted using VOSviewer, a bibliometric visualisation tool that generates network maps based on the frequency and co-occurrence of keywords. In these maps, node size represents keyword frequency, distances indicate relatedness, and clusters reflect thematic groupings within the research field.

The keyword co-occurrence analysis (Figure 4) reveals “scientific literacy” as the most central and dominant theme. Closely connected to this core theme is “digital literacy”, highlighting a strong research focus on integrating digital competencies into science education. This reflects the increasing recognition that scientific literacy in the digital era requires not only content knowledge but also digital skills.

Additional clusters reveal the prominence of socioscientific issues, critical thinking, and sustainability-related topics, indicating that scientific literacy research is increasingly addressing complex social and environmental challenges, such as climate change and misinformation. These themes position scientific literacy as a foundation for informed citizenship rather than solely academic achievement. The second cluster, blue and green, links the term “digital literacy” closely to science literacy, indicating a significant research trend toward integrating digital skills into science education. This trend reflects

the need for scientific understanding to include digital competencies, in line with the demands of the digital age (Mardiana, 2024).

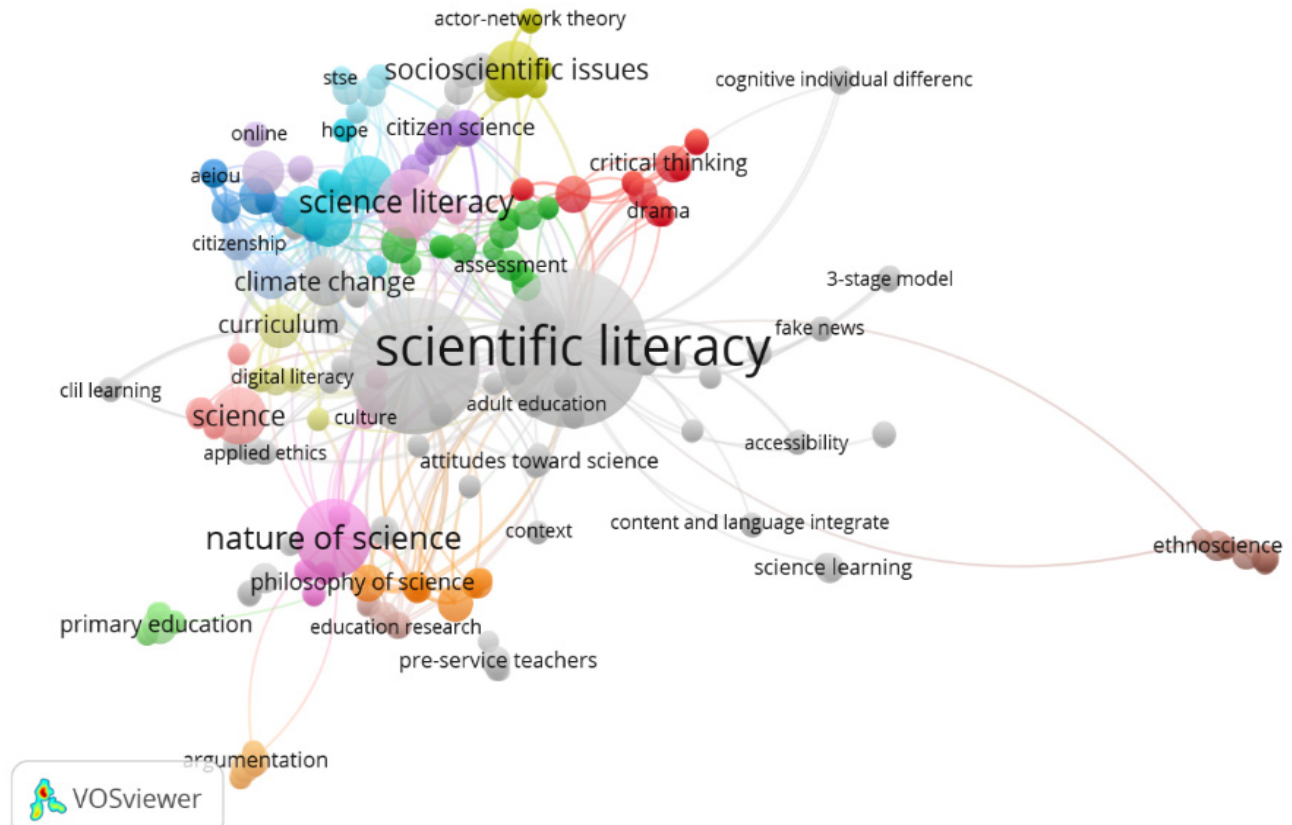


Figure 4. Co-occurrences for keywords in 2015-2024

The presence of “socioscientific issues” and “critical thinking” as the next cluster (purple) in red highlights the trend to address complex social and environmental issues through science education. These themes demonstrate the role of science literacy in understanding and debating issues such as climate change and fake news, which are increasingly relevant in a digital age where information is abundant and often misleading. The “ethnoscience” cluster, positioned on the far right, shows the focus on culturally relevant science education. Ethnoscience is concerned with integrating indigenous knowledge and local practices, which may be a response to a globalized digital world in which diverse cultural perspectives require recognition in scientific literacy (Sumarni et al., 2020).

Terms such as nature of science, philosophy of science, and argumentation (in orange and pink clusters) highlight the importance of understanding the processes and fundamentals of science. This trend reflects the digital age need for deeper critical engagement with science, where students not only absorb information but also understand scientific reasoning and construct arguments (Napal et al., 2020). The orange cluster refers to education and pre-service teacher research, indicating an interest in training future educators to teach science literacy more effectively. In this context, teachers who are proficient in using digital technologies and modern teaching methods to strengthen students’ scientific understanding are needed (Kroksmark, 2015).

Within the green and blue groups, terms such as “climate change” and “citizenship” strongly highlight the importance of science literacy in advancing informed citizenship. In the digital age, science literacy plays an important role in helping citizens understand and respond to pressing climate issues, especially as these topics are increasingly shared and discussed widely online (Tasquier et al., 2022). The existence of smaller gray areas under the terms ‘fake news’ and ‘accessibility’ illustrates the

serious challenges of misinformation in a digital context. This emphasizes the importance of research on scientific literacy to counter the spread of misinformation and ensure that scientific knowledge is accessible to all levels of society (Maia et al., 2021).

“Online” and ‘Curriculum Integration’ refer to efforts to incorporate digital learning into the curriculum, especially through online platforms. This reflects the adaptation of science education to fit the digital environment, making science learning more flexible and accessible (Serrano-Estrada et al., 2023). Assessment and Attitudes towards Science demonstrate the importance of evaluating the extent to which science literacy goals are achieved and of understanding students’ views on science.

In the digital age, assessment of digital and science literacy competencies is critical to improving educational outcomes (Silva et al., 2024). Overall, this visualization shows that science literacy research in the digital age covers a wide range of themes, from aspects of digital and scientific competence to critical evaluation of culturally relevant socioscientific and educational issues. The focus on topics such as fake news, climate change, and ethnoscience demonstrates the need to develop a critical and culturally sensitive understanding of science in a digitally evolving world. This holistic approach is a step towards scientific literacy that involves scientific content knowledge, digital skills, critical thinking, and cultural awareness, thus preparing individuals to thrive and actively participate in society.

RQ2: WHAT DIGITAL TOOLS AND METHODOLOGIES ARE COMMONLY USED TO DEVELOP SCIENTIFIC LITERACY IN MODERN SCIENCE EDUCATION?

To address RQ2, publications containing the keywords “scientific literacy”, “science education”, and “digital” were examined, resulting in a focused cohort of five highly relevant studies published between 2019 and 2024. The bibliometric results (Figure 5) indicate a strong association among scientific literacy, PjBL, digital learning environments, and technology-supported inquiry. PjBL emerges as a dominant pedagogical approach through which experiential and digital tools are operationalised to foster scientific literacy. Digital assessment games, digital learning systems, virtual learning environments, and interactive media are frequently reported as tools supporting PjBL-oriented science instruction.

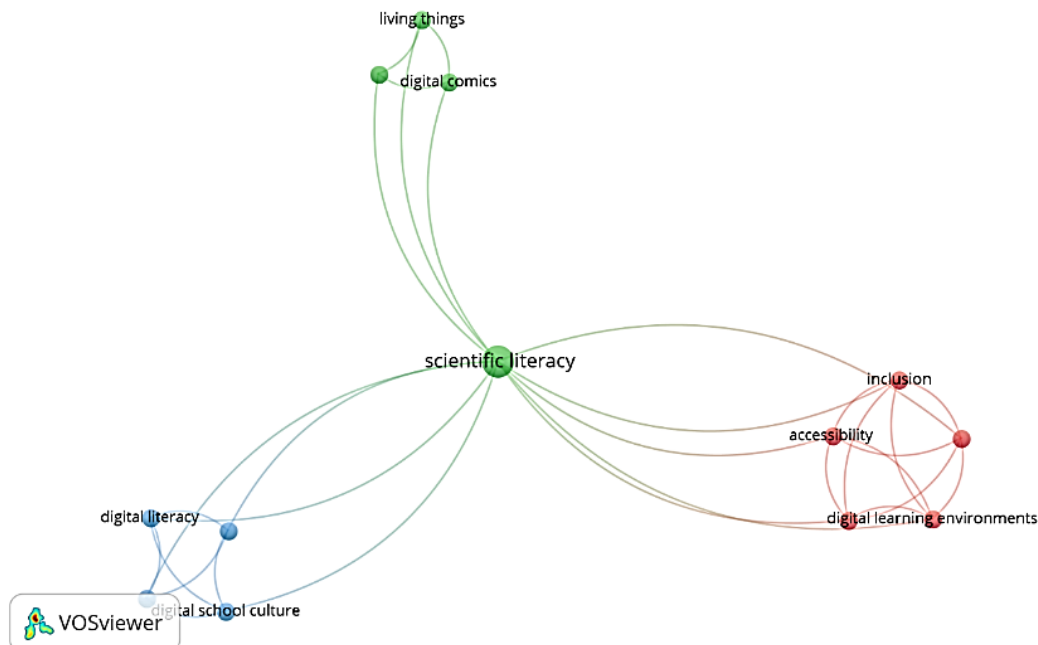


Figure 5. Relationship between keywords and co-citation

Bibliometric analysis can help identify the most cited articles that are considered influential in the development of digital scientific literacy. From these 5 articles, we can find out which digital tools or platforms are often recommended. These articles also discuss how to implement these tools in the science learning process, providing insight into best practices for developing scientific literacy. From the Co-Occurring Keywords and Co-Citation analysis, we can categorize digital tools based on their main function in developing scientific literacy. Table 3 shows the approach and grouping of digital tools based on Co-Occurring Keywords and Co-Citation. As summarised in Table 3, these tools are commonly used to promote active engagement, inquiry, and real-world problem-solving, key characteristics of project-based and experiential learning approaches that align with contemporary science education goals.

Table 3 shows that certain digital tools and methodologies have played an important role in developing scientific literacy in the digital era. The trend toward using digital assessment games, digital learning systems, digital learning environments, digital media, and digital technology can be explained as part of the effort to improve students' understanding of scientific concepts and to prepare them to think critically about scientific information in the digital world.

Table 3. List of proposals classified by co-occurring keywords, co-citation, methodology, and digital tools

Proposal title	Author (year)	Keywords	Co-citations	Method	Digital tools
An Evaluation of the Experimental Science Teaching Program for Primary Education from the Teachers' Perspective: An Educational Design Research Journey	(Silva et al., 2024)	educational design research; educational resources; primary education; science teaching	0	Educational design research methodological approach based on iterative cycles, with the collaboration of a multi-disciplinary team (e.g., teachers, researchers, and children)	digital assessment games
The Effect of Digital School Culture on Science Education and Scientific Literacy: A Scoping Review	(Litina & Rubene, 2024)	digital literacy; digital school culture; science education; scientific literacy; scoping review	0	Review to understand the impact of <i>digital</i> school culture on students' <i>scientific literacy</i> and science educational outcomes.	digital learning systems
Unveiling Potential: Fostering Students' Self-Concepts in Science Education by Designing Inclusive Educational Settings	(Graichen et al., 2024)	accessibility; digital learning environments; experimental instructions; inclusion; science for all; scientific literacy	0	Experimental instructions developed, and how these two concepts, accessibility and self-concept	digital learning environment

Proposal title	Author (year)	Keywords	Co-citations	Method	Digital tools
Digital comic teaching materials: Their role is to enhance students' literacy on organism characteristic topic	(Fitria et al., 2023)	digital comics; living things; science learning; scientific literacy	4	Using quasi-experimental research methods with a two-group pre-/post-test design	digital media
Socioscientific issues via controversy mapping: bringing actor-network theory into the science classroom with digital technology	(Elam et al., 2019)	Actor-network theory; citizenship education; controversy mapping; digital technology; interdisciplinary science education; socioscientific issues	11	This teaching innovation, called controversy mapping, has been pioneered in various higher education contexts before being adapted for school education. Experimenting with controversy mapping in a Swedish science class raised both conceptual and practical issues.	digital technology

RQ3: WHAT ARE THE IMPACTS OF DIGITAL LITERACY INTEGRATION ON STUDENTS' SCIENTIFIC LITERACY OUTCOMES?

The bibliometric map in Figure 6 shows strong thematic connections among scientific literacy, digital tools, and student learning outcomes. The findings suggest that integrating digital literacy supports students' conceptual understanding, critical thinking, and problem-solving abilities by enabling interactive exploration, data analysis, and visualisation of scientific phenomena.

In addition to cognitive outcomes, digital learning environments are associated with positive student attitudes and motivation toward science, which are important mediators of learning outcomes. These results indicate that digital literacy integration contributes to both cognitive and affective dimensions of scientific literacy development.

The relationship between digital tools and scientific literacy suggests that digital tools are actively used in science education, which may improve student learning outcomes. The use of digital platforms, such as apps and interactive devices, allows students to explore scientific concepts more interactively and in-depth. This direct student engagement with digital tools makes learning more dynamic and helps students retain and apply scientific concepts better. The relationship between digital literacy and scientific literacy suggests that integrating digital skills into science education can improve students' understanding of scientific concepts. With digital tools, students can visualize complex phenomena, simulate experiments, and analyse data, which helps deepen their understanding of science topics. For example, digital apps and simulations can make abstract scientific ideas more concrete, aiding conceptual understanding.

Learning analytics and meta-analysis are linked to science education, which implies a focus on data-driven insights into student performance (Redman et al., 2021). By using digital tools that involve data analysis, students develop critical thinking skills and problem-solving abilities (Behera et al., 2023). Engaging elements of digital literacy, such as data interpretation and analytical thinking, promote scientific reasoning as students learn to make evidence-based decisions and draw conclusions. The bibliometric map also shows student attitudes towards science and student learning outcomes as part of the science education network. It shows that digital literacy not only supports cognitive outcomes but also influences students' attitudes towards science. Digital learning environments often feel more familiar to students, fostering positive attitudes towards science subjects and increasing motivation and curiosity (Hobbs & Tuzel, 2017). These better attitudes correlate with better learning outcomes, as students become more likely to engage in scientific exploration.

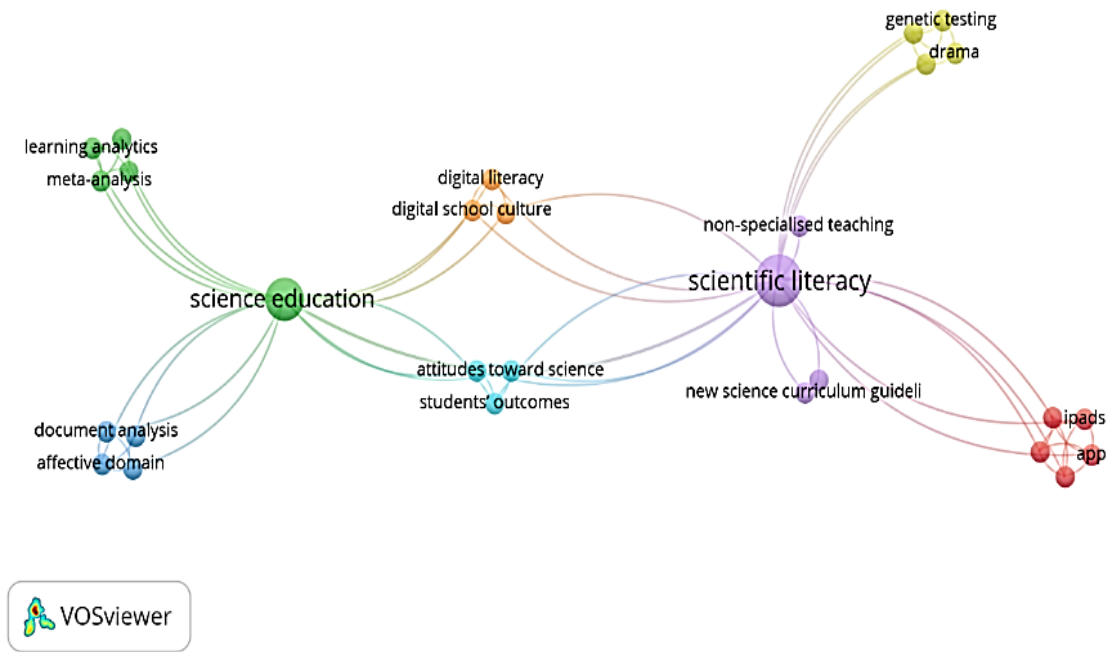


Figure 6. Main topic on scientific literacy in science education for the learning outcomes

RQ4: WHAT CHALLENGES DO EDUCATORS FACE IN INTEGRATING SCIENTIFIC AND DIGITAL LITERACY IN SCIENCE EDUCATION?

The analysis of 32 publications related to implementation challenges (Figure 7) shows that scientific literacy is closely linked to teacher competence, sustainability education, and curriculum alignment. Sustainability appears as a recurring challenge because effective scientific literacy instruction increasingly requires students to engage with complex environmental issues such as climate change and sustainable development.

Educators face challenges related to limited pedagogical competencies, assessment of complex skills (e.g., project-based scientific inquiry), and curriculum integration of sustainability-oriented digital content. These findings suggest that sustainability is not an isolated theme, but rather a contextual demand that intensifies the complexity of scientific and digital literacy integration.

In this figure, there are three main clusters that illustrate the relationship of relevant concepts. The green clusters show the close relationship between literacy, scientific knowledge, and sustainability. Within these clusters, concepts such as “sustainability,” “literacy,” and “knowledge” illustrate the

relationship between scientific literacy and sustainability issues, especially in the context of secondary education. At the secondary education level, teaching scientific literacy related to sustainability aims to equip students with the analytical and problem-solving skills needed to understand and deal with environmental issues (Bateman et al., 2021; Salinas et al., 2022). Scientific literacy-based teaching teaches students not only scientific facts, but also scientific ways of thinking, such as analyzing data, conducting experiments, and evaluating solutions from multiple perspectives, including their impact on sustainability (Väljataga & Mettis, 2022). A key challenge in integrating scientific and digital literacy is ensuring students understand sustainability issues, which requires a thorough understanding of scientific knowledge and environmentally relevant actions (Fitria et al., 2023).

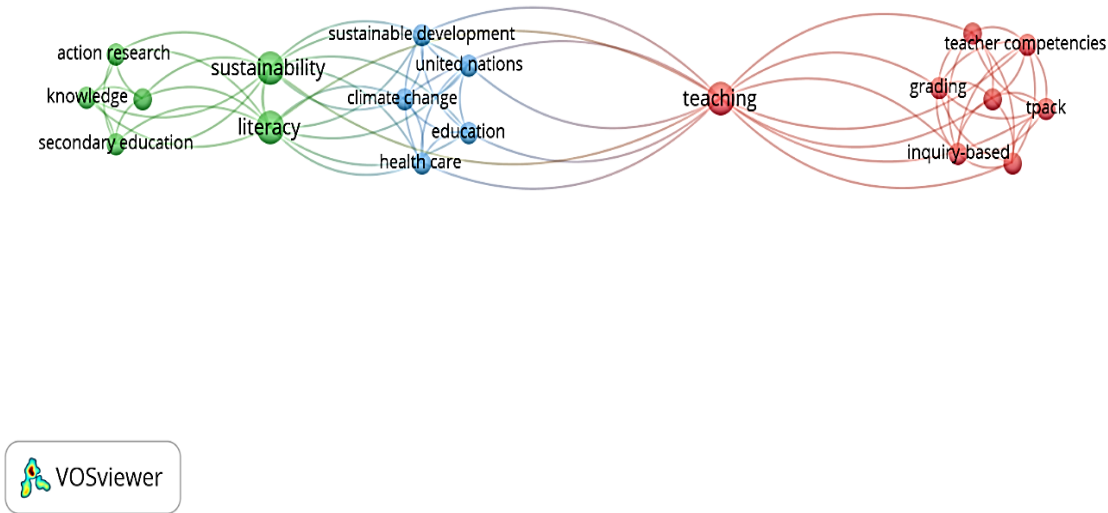


Figure 7. Main topic on scientific literacy in science education for the challenges for educators

The red cluster focuses on interconnected teaching and teacher competencies. This suggests that effective teaching in scientific and digital literacy requires specific competencies from educators, including the ability to apply inquiry-based methods that encourage students to think critically and analytically (Mierdel & Bogner, 2019; G. Zhang et al., 2022). The lack of these competencies is a challenge, especially when assessing complex skills, such as project-based scientific literacy (Romano et al., 2021). The blue cluster covers aspects of educational development and environmental issues, such as “climate change” and “sustainable development,” suggesting that scientific and digital literacy should be linked to global environmental issues to foster students’ understanding of how science impacts sustainability. A key challenge in this cluster is aligning curricula with environmental issues that often require an integrated scientific and digital approach. Adapting curricula to address issues such as climate change requires developing broader content and teaching methodologies (Bossér, 2024). Overall, the analysis shows that the challenges of integrating scientific and digital literacy in science education include developing teacher competencies, adjusting curricula, and evaluation methods that can effectively measure students’ scientific understanding and skills. Efforts to address these challenges are important to ensure holistically integrated scientific and digital literacy in students.

RQ 5: WHAT ARE THE FUTURE DIRECTIONS AND RECOMMENDATIONS FOR ENHANCING SCIENTIFIC LITERACY THROUGH DIGITAL TOOLS IN SCIENCE EDUCATION?

The bibliometric analysis (Figure 8) indicates that future research should focus on integrating digital tools with sustainability-oriented science curricula, inquiry-based learning, and teacher professional

development. Digital simulations, virtual laboratories, and data-driven inquiry platforms are highlighted as promising tools for enhancing students' engagement with real-world scientific challenges.

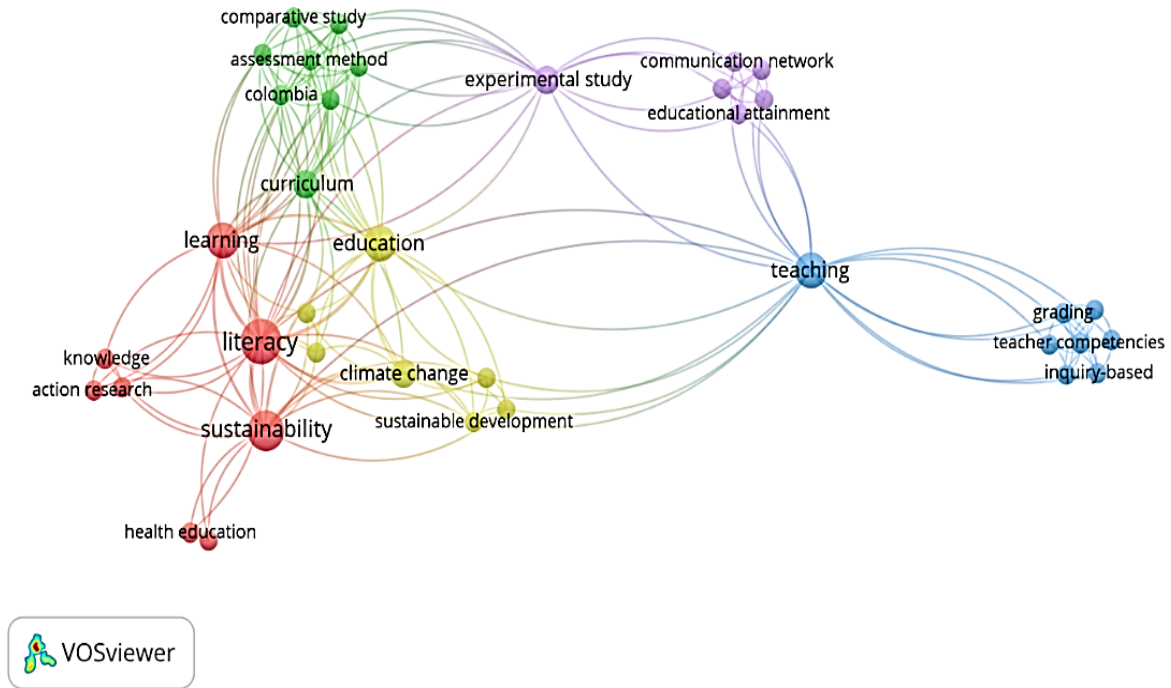


Figure 8. Main topic on scientific literacy in science education for the digital era

Science literacy encompasses one's ability to understand and use scientific concepts in everyday life. The presence of "curriculum" and "inquiry-based" clusters indicates a trend towards curricula that emphasize critical thinking and hands-on inquiry. In the future, educators need to design curricula that combine scientific literacy with digital inquiry tools, such as virtual experiments, online research databases, and collaborative platforms (Mardiana, 2024). This approach allows students to develop digital research skills and apply them to scientific questions, thus improving their understanding of scientific concepts.

The bibliometric map highlights "teacher competence" and "teaching" as important elements. The development of digital literacy among educators is critical because of their key role in implementing and guiding digital tools in science classrooms (J. Zhang & Yu, 2022). Professional development programs should be expanded to equip teachers with digital competencies, including the use of educational software, data analysis tools, and online collaboration platforms (Althubayani, 2024). This training ensures that teachers can effectively integrate digital resources in their instruction to improve scientific literacy. The map also shows "comparative studies" and "experimental studies" as significant nodes, indicating the need for rigorous research design. The way forward should involve more comparative and experimental studies to assess the effectiveness of specific digital tools in improving scientific literacy. By identifying the effectiveness of digital tools in different contexts, these studies can guide evidence-based policy and recommendations for digital integration in science education (Schiff, 2020).

The "assessment methods" node indicates the need for further research on the evaluation of digital and scientific literacy skills. Future research should explore new assessment frameworks that measure scientific understanding and digital skills. Digital assessments that involve data analysis, online research, and problem-solving can provide a deeper understanding of students' abilities in digital and scientific contexts (Rohm et al., 2019). One important step is to integrate sustainability and climate

topics into science education through digital tools, design curricula that emphasize digital and scientific inquiry, strengthen teacher training programs in digital literacy, and conduct more experimental and comparative studies to improve evidence-based approaches.

Furthermore, the prominence of assessment-related keywords suggests the need for innovative evaluation frameworks that capture both scientific and digital literacy competencies. Overall, future research should prioritise experimental and comparative studies to strengthen evidence-based practices in digital science education.

CONCLUSIONS

This bibliographic analysis highlights a clear shift in contemporary science education research toward integrating digital competencies with scientific literacy. Consistent with international literature, recent studies increasingly conceptualise scientific literacy not merely as content knowledge, but as a multi-dimensional capacity that includes critical evaluation, socioscientific reasoning, and responsible citizenship in digitally mediated contexts.

Although publication output has increased, the decline in citation rates observed in recent years should be interpreted cautiously, as newer studies require time to accumulate scholarly impact. Nevertheless, this pattern raises important questions about the translation of research insights into sustained educational practices and their long-term influence on science education.

The synthesis further reveals a persistent gap between conceptual discussions and practical implementation. While digital literacy and socioscientific issues are widely acknowledged, integrative learning models that connect scientific literacy and digital skills in authentic contexts remain limited. This gap is particularly consequential given global challenges such as misinformation, climate change, and complex socio-environmental decision-making, which demand that learners engage critically with scientific information in digital spaces.

Key challenges identified include limited interdisciplinary integration, insufficient teacher professional development, and fragmented curriculum designs that fail to align scientific, digital, and media literacy. Addressing these issues requires coordinated and systemic efforts rather than isolated pedagogical interventions.

Accordingly, this study emphasises the need for collaboration among educators, policymakers, curriculum developers, and technology experts to create coherent educational ecosystems. Aligning science curricula with digital literacy and critical thinking, strengthening teacher professional development, and adopting interdisciplinary instructional frameworks are essential for empowering learners as informed and responsible citizens. Future research should extend beyond bibliographic analyses toward empirical and design-based studies to evaluate the effectiveness of such integrative approaches across diverse educational contexts.

REFERENCES

- Althubyani, A. R. (2024). Digital competence of teachers and the factors affecting their competence level: A nationwide mixed-methods study. *Sustainability*, 16(7), 2796. <https://doi.org/10.3390/su16072796>
- Anuar, A. M. (2025). Instances of dis/juncture: STEM education and young people's aspirations for development in the Malaysian *luar bandar*. *Compare: A Journal of Comparative and International Education*, 55(8), 1364–1381. <https://doi.org/10.1080/03057925.2023.2254210>
- Arifin, Z., Sukarmin, S., & Saputro, S. (2025). Trends and research frontiers in socioscientific issues for sustainable science education: A systematic and bibliometric analysis from 2014 – 2024. *Journal of Pedagogical Research*, 9(1), 407–434. <https://doi.org/10.33902/JPR.202530575>
- Bateman, K. M., Steele, D., & Sexton, C. M. (2021). Sustainability science education: Our animalistic responsibility. *Cultural Studies of Science Education*, 16, 841–855. <https://doi.org/10.1007/s11422-021-10039-7>

- Behera, A. K., de Sousa, R. A., Oleksik, V., Dong, J., & Fritzen, D. (2023). Student perceptions of remote learning transitions in engineering disciplines during the COVID-19 pandemic: A cross-national study. *European Journal of Engineering Education*, 48(1), 110–142. <https://doi.org/10.1080/03043797.2022.2080529>
- Bidarra, J., & Rusman, E. (2017). Towards a pedagogical model for science education: Bridging educational contexts through a blended learning approach. *Open Learning: The Journal of Open, Distance and e-Learning*, 32(1), 6–20. <https://doi.org/10.1080/02680513.2016.1265442>
- Bossér, U. (2024). Transformation of school science practices to promote functional scientific literacy. *Research in Science Education*, 54(2), 265–281. <https://doi.org/10.1007/s11165-023-10138-1>
- BPIKA. (2024). *Lo Kreatif: Tema Global Innovation Challenge, Fostering Sustainable, Futures, SDGS and Futuretechnologies*. <https://bpika.uma.ac.id/2024/07/03/lo-kreatif-2024-tema-global-innovation-challenge-fostering-sustainable-futures-sdgs-and-futuretechnologies/>
- Chu, S. K. W., Reynolds, R. B., Tavares, N. J., Notari, M., & Lee, C. W. Y. (2016). *21st century skills development through inquiry-based learning: From theory to practice*. Springer. <https://doi.org/10.1007/978-981-10-2481-8>
- Costas, R., Zahedi, Z., & Wouters, P. (2015). The thematic orientation of publications mentioned on social media: Large-scale disciplinary comparison of social media metrics with citations. *Aslib Journal of Information Management*, 67(3), 260–288. <https://doi.org/10.1108/AJIM-12-2014-0173>
- Dalky, A., Altawalbih, M., Alshanik, F., Khasawneh, R. A., Tawalbeh, R., Al-Dekah, A. M., Alrawashdeh, A., Quran, T. O., & ALBashtawy, M. (2025). Global research trends, hotspots, impacts, and emergence of artificial intelligence and machine learning in health and medicine: A 25-year bibliometric analysis. *Healthcare*, 13(8), 892. <https://doi.org/10.3390/healthcare13080892>
- de Andrade Gomes, J., Braga, L. A. M., Cabral, B. P., Lopes, R. M., & Mota, F. B. (2024). Problem-based learning in medical education: A global research landscape of the last ten years (2013–2022). *Medical Science Educator*, 34, 551–560. <https://doi.org/10.1007/s40670-024-02003-1>
- Donthu, N., Kumar, S., Mukherjee, D., Pandey, N., & Lim, W. M. (2021). How to conduct a bibliometric analysis: An overview and guidelines. *Journal of Business Research*, 133, 285–296. <https://doi.org/10.1016/j.jbusres.2021.04.070>
- Elam, M., Solli, A., & Mäkitalo, Å. (2019). Socioscientific issues via controversy mapping: Bringing actor-network theory into the science classroom with digital technology. *Discourse*, 40(1), 61–77. <https://doi.org/10.1080/01596306.2018.1549704>
- Falloon, G. (2020). From digital literacy to digital competence: The teacher digital competency (TDC) framework. *Educational Technology Research and Development*, 68, 2449–2472. <https://doi.org/10.1007/s11423-020-09767-4>
- Farias-Gaytan, S., Aguaded, I., & Ramirez-Montoya, M. S. (2023). Digital transformation and digital literacy in the context of complexity within higher education institutions: A systematic literature review. *Humanities and Social Sciences Communications*, 10, 386. <https://doi.org/10.1057/s41599-023-01875-9>
- Fitria, Y., Malik, A., Mutiaramses, Halili, S. H., & Amelia, R. (2023). Digital comic teaching materials: It's role to enhance student's literacy on organism characteristic topic. *Eurasia Journal of Mathematics, Science and Technology Education*, 19(10), em2333. <https://doi.org/10.29333/ejmste/13573>
- Fortus, D., Lin, J., Neumann, K., & Sadler, T. D. (2022). The role of affect in science literacy for all. *International Journal of Science Education*, 44(4), 535–555. <https://doi.org/10.1080/09500693.2022.2036384>
- Giri, V., & Paily, M. U. (2020). Effect of scientific argumentation on the development of critical thinking. *Science and Education*, 19(3), 673–690. <https://doi.org/10.1007/s11191-020-00120-y>
- Gizaw, G. G., & Sota, S. S. (2023). Improving science process skills of students: A review of literature. *Science Education International*, 34(3), 216–224. <https://doi.org/10.33828/sci.v34.i3.5>
- González-Zamar, M.-D., Abad-Segura, E., López-Meneses, E., & Gómez-Galán, J. (2020). Managing ICT for sustainable education: Research analysis in the context of higher education. *Sustainability*, 12(19), 8254. <https://doi.org/10.3390/su12198254>

- Graichen, M., Mikelskis-Seifert, S., Hinderer, L., Scharenberg, K., & Rollett, W. (2024). Unveiling potential: Fostering students' self-concepts in science education by designing inclusive educational settings. *Education Sciences*, 14(6), 632. <https://doi.org/10.3390/educsci14060632>
- Gultepe, N., & Kilic, Z. (2015). Effect of scientific argumentation on the development of scientific process skills in the context of teaching chemistry. *International Journal of Environmental and Science Education*, 10(1),(PISA 2012), 111–132. <https://doi.org/10.12973/ijese.2015.234a>
- Hobbs, R., & Tuzel, S. (2017). Teacher motivations for digital and media literacy: An examination of Turkish educators. *British Journal of Educational Technology*, 48(1), 7–22. <https://doi.org/10.1111/bjet.12326>
- Hoesny, M. U., Setyosari, P., Praherdhiono, H., & Suryati, N. (2024). Integrating digital technology into project-based learning: Its impact on speaking performance. *Mextesol Journal*, 48(3), 1–11. <https://doi.org/10.61871/mj.v48n3-4>
- Hurd, P. D. (1998). Scientific literacy: New minds for a changing world. *Science Education*, 82(3), 407–416. [https://doi.org/10.1002/\(SICI\)1098-237X\(199806\)82:3<407::AID-SCE6>3.3.CO;2-Q](https://doi.org/10.1002/(SICI)1098-237X(199806)82:3<407::AID-SCE6>3.3.CO;2-Q)
- Ibrahim, A. (2025). Identifying gaps and contributions of project-based learning in vocational education and STEM fields: A comprehensive bibliometric analysis. *Journal of Scientometric Research*, 14(1), 86–98. <https://doi.org/10.5530/jscires.20250763>
- Jia, N., Luo, X., Fang, Z., & Liao, C. (2024). When and how artificial intelligence augments employee creativity. *Academy of Management Journal*, 67(1). <https://doi.org/10.5465/amj.2022.0426>
- Kaldaras, L., Haudek, K., & Krajcik, J. (2024). Employing automatic analysis tools aligned to learning progressions to assess knowledge application and support learning in STEM. *International Journal of STEM Education*, 11, Article 57. <https://doi.org/10.1186/s40594-024-00516-0>
- Kavitha, K., & Joshith, V. P. (2024). Pedagogical incorporation of artificial intelligence in K-12 science education: A decadal bibliometric mapping and systematic literature review (2013-2023). *Journal of Pedagogical Research*, 8(4), 437–465. <https://doi.org/10.33902/JPR.202429218>
- Korneeva, E., Strielkowski, W., Krayneva, R., & Sherstobitova, A. (2022). Social health and psychological safety of students involved in online education during the COVID-19 pandemic. *International Journal of Environmental Research and Public Health*, 19(21), 13928. <https://doi.org/10.3390/ijerph192113928>
- Kroksmark, T. (2015). Teachers' subject competence in digital times. *Education Inquiry*, 6(1), Article 24013. <https://doi.org/10.3402/edui.v6.24013>
- Lame, G. (2019). Systematic literature reviews: An introduction. *Proceedings of the Design Society: International Conference on Engineering Design*, 1(1), 1633–1642. <https://doi.org/10.1017/dsi.2019.169>
- Lee, K. A., Lee, J. R., & Bell, P. (2020). A review of Citizen Science within the Earth Sciences: Potential benefits and obstacles. *Proceedings of the Geologists' Association*, 131(6), 605–617. <https://doi.org/10.1016/j.pgeola.2020.07.010>
- Lembens, A., & Krebs, R. E. (2025). Analysing and developing linguistically responsive tasks within the framework of the cross-disciplinary Erasmus+ project sensiMINT. *Chemistry Teacher International*, 7(1), 19–30. <https://doi.org/10.1515/cti-2022-0041>
- Litina, S., & Rubene, Z. (2024). The effect of digital school culture on science education and scientific literacy: A scoping review. *Journal of Education Culture and Society*, 15(1), 41–55. <https://doi.org/10.15503/jecs2024.1.41.55>
- Maia, P., Justi, R., & Santos, M. (2021). Aspects about science in the context of production and communication of knowledge of COVID-19. *Science and Education*, 30(5), 1075–1098. <https://doi.org/10.1007/s11191-021-00229-8>
- Maier, U., & Klotz, C. (2022). Personalized feedback in digital learning environments: Classification framework and literature review. *Computers and Education: Artificial Intelligence*, 3, 100080. <https://doi.org/10.1016/j.caeai.2022.100080>
- Mardiana, H. (2024). Perceived impact of lecturers' digital literacy skills in higher education institutions. *Sage Open*, 14(3). <https://doi.org/10.1177/21582440241256937>

- Melgaard, J., Monir, R., Lasrado, L. A., & Fagerstrøm, A. (2021). Academic procrastination and online learning during the COVID-19 pandemic. *Procedia Computer Science*, 196, 117–124. <https://doi.org/10.1016/j.procs.2021.11.080>
- Mendoza, J., & Wagner, K. (2025). Gold Standard Project Based Learning designed as HQIM. *PBLWork*, 4(1), 1–7. https://www.pblworks.org/sites/default/files/2025-02/Gold%20Standard%20Project%20Based%20Learning%20designed%20as%20HQIM_2025%20%20.pdf
- Mierdel, J., & Bogner, F. X. (2019). Comparing the use of two different model approaches on students' understanding of DNA models. *Education Sciences*, 9(2), 115. <https://doi.org/10.3390/educsci9020115>
- Napal, M., Mendióroz-Lacambra, A. M., & Peñalva, A. (2020). Sustainability teaching tools in the digital age. *Sustainability*, 12(8), 3366. <https://doi.org/10.3390/SU12083366>
- Norambuena-Meléndez, M., Guerrero, G. R., & González-Weil, C. (2023). What is meant by scientific literacy in the curriculum? A comparative analysis between Bolivia and Chile. *Cultural Studies of Science Education*, 18(3), 937–958. <https://doi.org/10.1007/s11422-023-10190-3>
- OECD. (2019). *PISA 2018 assessment and analytical framework*. OECD Publishing. <https://doi.org/10.1787/b25efab8-en>
- Page, M. J., Moher, D., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., ... McKenzie, J. E. (2021). PRISMA 2020 explanation and elaboration: Updated guidance and exemplars for reporting systematic reviews. *BMJ*, 372(160). <https://doi.org/10.1136/bmj.n160>
- Redman, C. M., Tomiya, S., Bitterman, K., Cain, K., & Meachen, J. A. (2021). Utilizing inquiry-driven science outreach to curate Natural Trap Cave fossils and inspire the pursuit of STEM careers. *Evolution: Education and Outreach*, 14, Article 13. <https://doi.org/10.1186/s12052-021-00152-0>
- Rehman, N., Huang, X., Mahmood, A., AlGerafi, M. A. M., & Javed, S. (2024). Project-based learning as a catalyst for 21st-Century skills and student engagement in the math classroom. *Heliyon*, 10(23), e39988. <https://doi.org/10.1016/j.heliyon.2024.e39988>
- Rohm, A. J., Stefl, M., & Saint Clair, J. (2019). Time for a marketing curriculum overhaul: Developing a digital-first approach. *Journal of Marketing Education*, 41(1), 47–59. <https://doi.org/10.1177/0273475318798086>
- Romano, M. R., Díaz-Almeyda, E., Namdul, T., & Lhundup, Y. (2021). Dialogue-based learning: A framework for inclusive science education and applied ethics. *Frontiers in Communication*, 6, Article 731839. <https://doi.org/10.3389/fcomm.2021.731839>
- Safrizal, S., Sudarmono, & Yulia, R. (2022). Developing students science literacy in Adiwiyata School: Case study in Padang City, Indonesia. *Journal of Turkish Science Education*, 19(4), 1192–1205. <https://doi.org/10.36681/tused.2022.169>
- Salinas, I., Guerrero, G., Satlov, M., & Hidalgo, P. (2022). Climate change in Chile's school science curriculum. *Sustainability*, 14(22), 15212. <https://doi.org/10.3390/su142215212>
- Schiffl, I. (2020). How information literate are junior and senior class biology students? *Research in Science Education*, 50, 773–789. <https://doi.org/10.1007/s11165-018-9710-2>
- Selcuk, A. A. (2019). A guide for systematic reviews: PRISMA. *Turkish Archives of Otorhinolaryngology*, 57(1), 57–58. <https://doi.org/10.5152/tao.2019.4058>
- Serrano-Estrada, L., Martin, T. J., & Marti, P. (2023). Understanding city dynamics: Using geolocated social media in a problem-based activity as an investigative tool to enhance student learning. *Journal of Geography in Higher Education*, 47(1), 106–127. <https://doi.org/10.1080/03098265.2021.2004390>
- Silva, P. C., Rodrigues, A. V., & Vicente, P. N. (2024). An evaluation of the experimental science teaching program for primary education from the teachers' perspective: An educational design research journey. *Education Sciences*, 14(7), 782. <https://doi.org/10.3390/educsci14070782>

- Stalmach, A., D'Elia, P., Di Sano, S., & Casale, G. (2024). Digital methods to promote inclusive and effective learning in schools: A mixed methods research study. *Open Education Studies*, 6(1), 20240023. <https://doi.org/10.1515/edu-2024-0023>
- Sumarni, W., Faizah, Z., Subali, B., Wiyanto, W., & Ellianawati. (2020). The urgency of religious and cultural science in stem education: A meta data analysis. *International Journal of Evaluation and Research in Education*, 9(4), 1045–1054. <https://doi.org/10.11591/ijere.v9i4.20462>
- Tasquier, G., Knain, E., & Jornet, A. (2022). Scientific literacies for change making: Equipping the young to tackle current societal challenges. *Frontiers in Education*, 7, 689329. <https://doi.org/10.3389/feduc.2022.689329>
- Thelma, C. C., Sain, Z. H., & Shogbesan, Y. O., Phiri, E. V., & Akpan, W. M. (2024). Digital literacy in education: Preparing students for the future workforce. *International Journal of Research*, 11(8), 327-344. <https://doi.org/10.5281/ZENODO.13347718>
- Tran, T., Ho, M.-T., Pham, T.-H., Nguyen, M.-H., Nguyen, K.-L. P., Vuong, T.-T., Nguyen, T.-H. T., Nguyen, T.-D., Nguyen, T.-L., Khuc, Q., La, V.-P., & Vuong, Q.-H. (2020). How digital natives learn and thrive in the digital age: Evidence from an emerging economy. *Sustainability*, 12(9), 3819. <https://doi.org/10.3390/su12093819>
- Turiman, P., Omar, J., Daud, A. M., & Osman, K. (2012). Fostering the 21st century skills through scientific literacy and science process skills. *Procedia - Social and Behavioral Sciences*, 59, 110–116. <https://doi.org/10.1016/j.sbspro.2012.09.253>
- UNESCO Institute for Statistics. (2025). *Data for the sustainable development goals*. <https://www.uis.unesco.org/en>
- Väljätaga, T., & Mettis, K. (2022). Secondary education students' knowledge gain and scaffolding needs in mobile outdoor learning settings. *Sustainability*, 14(12), 7031. <https://doi.org/10.3390/su14127031>
- Varas, D., Santana, M., Nussbaum, M., Claro, S., & Imbarack, P. (2023). Teachers' strategies and challenges in teaching 21st century skills: Little common understanding. *Thinking Skills and Creativity*, 48, 101289. <https://doi.org/10.1016/j.tsc.2023.101289>
- Vasquez, S., & Atwood, E. D. (2023). Science for some: Examining representations of relevancy and multiculturalism in Texas biology standards and textbooks. *Frontiers in Education*, 8, 1076751. <https://doi.org/10.3389/feduc.2023.1076751>
- Veginadu, P., Calache, H., Gussy, M., Pandian, A., & Masood, M. (2022). An overview of methodological approaches in systematic reviews. *Journal of Evidence-Based Medicine*, 15(1), 39–54. <https://doi.org/10.1111/jebm.12468>
- Vuorikari, R., Kluzer, S., & Punie, Y. (2022). *DigComp 2.2. The Digital Competence framework for citizens. With new examples of knowledge, skills and attitudes*. European Commission. <https://doi.org/10.2760/115376>
- Zhang, G., Li, Y., Zhou, G., & Ho, S. W.-Y. (2022). Exploring pre-service science teachers' perspectives on the nature of science: A comparative study between China and Canada. *ECNU Review of Education*, 5(3), 520–536. <https://doi.org/10.1177/2096531120966782>
- Zhang, J., & Yu, S. (2022). Assessing the innovation of mobile pedagogy from the teacher's perspective. *Sustainability*, 14(23), 15676. <https://doi.org/10.3390/su142315676>
- Zhang, L., & Ma, Y. (2023). A study of the impact of project-based learning on student learning effects: A meta-analysis study. *Frontiers in Psychology*, 14, 1202728. <https://doi.org/10.3389/fpsyg.2023.1202728>

AUTHORS



Nuraida is a doctoral candidate in Science Education at Universitas Sebelas Maret (UNS), Surakarta, Indonesia. She holds a Master's degree in Science Education from Universitas Negeri Surabaya (UNESA). Her research focuses on applied science, particularly theoretical and science education, innovation in science learning, curriculum development, and technology integration. With teaching experience at both secondary and tertiary levels, her research interests span theoretical physics and physics education. Her current dissertation explores scientific literacy.

Email: aidanur2@student.uns.ac.id ORCID: 0009-0008-1869-5062



Prof. Dra. Soeparmi, MA, PhD, is a Professor in the Department of Physics, Universitas Sebelas Maret, Indonesia. She earned her PhD in Science Education from SUNY Albany and her Masters from SUNY New Paltz. Her research interests include theoretical physics, quantum mechanics, wave equations, position-dependent mass systems, quantum dots, and physics education. She has published extensively in Scopus-indexed journals and has an h-index of 12. ORCID: 0000-0001-8395-4309



Prof. Dr. Widha Sunarno, SPd, MPd, is a Professor of Physics Education at Universitas Sebelas Maret (UNS), Surakarta, Indonesia. His expertise includes science learning innovation, instructional model development, science process skills, and physics education assessment. With extensive publications in reputable national and international journals, his research significantly advances physics and science education, particularly in learning quality enhancement, critical thinking development, and research-based instructional design. ORCID: 0000-0001-8264-3509



Dr.rer.nat. Sri Mulyani, M.Si., is a chemist specializing in chemistry education, natural product chemistry, green synthesis, and applied biomolecular research. She earned her doctorate in biochemistry from Technische Universität Dresden, a master's degree in science from the Bandung Institute of Technology, and a bachelor's degree in chemistry education from the IKIP Yogyakarta. Her research focuses on sustainable bioactive compounds, antibacterial and antioxidant agents, food security biomaterials, biogas enhancement, and innovation in chemistry education. She has published extensively in peer-reviewed journals on molecular docking, green chemistry, natural product utilization, diagnostic assessment, and STEM learning. Email: srimumlyaniuns@staff.uns.ac.id ORCID: 0000-0002-0181-1345