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# Assessing the Landscape of Scientific Literacy in Formal Education: A Systematic Review

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**Abstract:**

This systematic review synthesizes empirical studies on scientific literacy published in peer-reviewed journals between 2001 and 2022. It investigates how scientific literacy is conceptualized and developed across different levels of formal education and examines implications for strengthening its foundations in early childhood contexts. Using PRISMA-guided procedures, an initial pool of 500 articles was screened, resulting in 45 studies that met the inclusion criteria for final analysis. The findings reveal a strong concentration of research within secondary and higher education, with a predominant reliance on quantitative methodologies such as standardized assessments and surveys. Across the reviewed studies, three major themes emerged: the effectiveness of instructional programs and interventions in enhancing scientific literacy, the measurement of literacy levels among students and teachers, and the influence of external factors such as cognitive abilities, socio-economic background, and learning environments. Despite these insights, the review identifies a significant research gap in early years education, particularly in relation to play-based pedagogy, cultural context, and learner-centered approaches. The study concludes that future research should expand its focus to include early childhood settings and adopt more diverse methodologies to better capture the developmental nature of scientific literacy.

*Keywords:* scientific literacy; systematic review; early childhood education; science education; quantitative research; PRISMA; instructional strategies; educational development

**Introduction:**

Scientific literacy is widely recognized as a fundamental competency in contemporary education, referring to an individual's ability to understand scientific concepts and apply them in everyday decision-making and socio-scientific contexts. In an increasingly complex and technology-driven world, fostering scientific literacy is essential for developing a population capable of critical thinking, informed judgment, and responsible citizenship. Scholars emphasize that scientific literacy extends beyond content knowledge, encompassing skills such as reasoning, communication, and the evaluation of evidence in real-world situations (Li, Y. & Guo, M., 2021; Cavagnetto, A. R., 2010).

The growing body of literature highlights that early engagement in science learning plays a crucial role in shaping long-term scientific literacy. Experiences in early childhood particularly those involving inquiry, exploration, and play serve as foundational building blocks for later scientific understanding and attitudes toward science. Research suggests that introducing meaningful science activities during preschool years enhances curiosity, problem-solving skills, and the ability to make connections between scientific ideas and everyday experiences (Bramastia, B. & Rahayu, S., 2023).

However, scientific literacy is not a singular or easily measurable construct; rather, it is shaped by multiple interacting factors, including educational environments, teaching practices, parental involvement, and socio-cultural contexts. Studies have demonstrated that approaches such as project-based learning, argumentation, and the integration of socio-scientific issues significantly enhance students' scientific literacy by promoting deeper engagement and critical thinking (Hudha, M. N. et al., 2023; Kumar, V. et al., 2024). These approaches position learners not merely as recipients of knowledge but as active participants in constructing scientific understanding.

In addition, the incorporation of real-world issues such as environmental challenges and climate change has been identified as an effective context for developing scientific literacy. Engaging learners with authentic socio-scientific issues encourages them to apply scientific knowledge in meaningful ways while considering ethical, social, and global implications. For instance, climate literacy frameworks highlight the importance of integrating interdisciplinary knowledge to address complex global concerns (Azevedo, J. & Marques, M., 2017).

Despite these advances, much of the existing research on scientific literacy has focused predominantly on primary, secondary, and higher education levels, often overlooking the early years of formal education. This imbalance limits the field's understanding of how scientific literacy develops from its earliest stages and how early interventions can support continuous learning trajectories. Furthermore, recent literature points to the need for more classroom-based and context-sensitive studies that capture how scientific literacy is enacted in diverse educational settings (Yanto, N. & Sari, N. I., 2025).

Given these gaps, this systematic review aims to examine how scientific literacy is constructed across different levels of formal education and to identify emerging trends, methodological approaches, and underexplored areas particularly in early childhood contexts. By synthesizing empirical evidence, this study seeks to contribute to a more comprehensive understanding of scientific literacy development and to provide insights that can inform future research, policy, and practice in early years science education.

**Literature Review:**

Scientific literacy has evolved from a narrow focus on content knowledge to a multidimensional construct encompassing critical thinking, communication, and the ability to engage with socio-scientific issues. Contemporary perspectives emphasize that scientifically literate individuals must not only understand scientific concepts but also evaluate information, participate in public discourse, and make informed decisions in complex societal contexts. This shift reflects broader educational goals aligned with preparing learners for the demands of the 21st century (Li, Y. & Guo, M., 2021).

A growing body of research highlights the role of socio-scientific issues (SSI) in enhancing scientific literacy by situating learning within real-world contexts. SSI-based instruction encourages learners to analyze controversial and complex issues such as environmental sustainability, thereby fostering critical reasoning and ethical reflection. A systematic review by Kumar, V. et al. (2024) demonstrates that integrating environmental issues into science education significantly strengthens students' engagement and application of scientific knowledge in authentic contexts.

Instructional strategies play a central role in shaping scientific literacy outcomes. Project-based learning (PBL), for instance, has been widely recognized as an effective approach for promoting inquiry, collaboration, and problem-solving skills. According to Hudha, M. N. et al. (2023), PBL fosters deeper conceptual understanding by allowing students to actively construct knowledge through meaningful tasks. Similarly, critical reviews indicate that diverse learning models, including inquiry-based and problem-based approaches, contribute significantly to improving scientific literacy (Saputra, W. T. et al., 2024).

Another important dimension of scientific literacy development is argumentation. The ability to construct, evaluate, and defend scientific arguments is essential for engaging in evidence-based reasoning. Cavagnetto, A. R. (2010) highlights that argument-based interventions in K–12 settings improve students' analytical thinking and understanding of scientific concepts. This aligns with broader efforts to move beyond rote learning toward more dialogic and interactive science classrooms.

Research also underscores the strong relationship between scientific literacy and critical thinking skills. A scoping review by Bramastia, B. and Rahayu, S. (2023) found that instructional approaches grounded in scientific literacy frameworks significantly enhance learners' ability to analyze, evaluate, and synthesize information. These findings reinforce the notion that scientific literacy is not an isolated competency but is closely intertwined with higher-order cognitive processes.

Despite these advancements, several studies point to persistent challenges in the implementation of scientific literacy-oriented instruction. Sukiastini, I. G. A. N. K. et al. (2025) identify issues such as limited teacher preparedness, lack of resources, and curriculum constraints as barriers to effective integration. Similarly, Romli, S. et al. (2024) note that while innovative learning models are being developed, their practical application remains inconsistent across educational contexts.

Recent literature has also expanded the scope of scientific literacy to include interdisciplinary and emerging domains. Climate literacy, for example, integrates scientific understanding with global awareness and sustainability practices. Azevedo, J. and Marques, M. (2017) emphasize the importance of equipping learners with the knowledge and skills necessary to address climate-related challenges. Similarly, computational literacy has been identified as an increasingly important component of science education in the digital age (Braun, D. & Huwer, J., 2022).

The integration of literacy across disciplines further highlights the evolving nature of scientific literacy. Studies have shown that language development and literacy skills significantly influence students' ability to understand and communicate scientific ideas. For instance, Heryani, R. et al. (2024) demonstrate that children's literature can be an effective tool for promoting both language and scientific literacy in early education settings. This interdisciplinary approach supports more holistic learning experiences.

Moreover, the role of media and digital platforms in shaping scientific literacy has gained increasing attention. In an era characterized by the rapid dissemination of information, the ability to critically evaluate scientific content online is essential. Rosenthal, S. (2020) argues that media literacy is closely linked to scientific literacy, particularly in navigating science-related content on digital platforms. This highlights the need for educational frameworks that address both domains simultaneously.

Emerging perspectives also emphasize the importance of community and societal dimensions of scientific literacy. Busch, K. C. and Rajwade, A. (2024) propose the concept of community scientific literacy, which extends beyond individual competencies to include collective understanding and participation. Additionally, alternative visions such as Vision III advocate for a more holistic approach that integrates ethical, socio-political, and existential dimensions of science education (Sjöström, J., 2025).

Finally, critical reviews highlight the need to re-examine the philosophical foundations of scientific literacy. Kilag, O. K. et al. (2023) argue for a Bildung-oriented approach that emphasizes personal development, values formation, and the transformative potential of education. This perspective challenges traditional utilitarian views and calls for a more humanistic and reflective understanding of scientific literacy.

The literature reveals that scientific literacy is a dynamic and evolving construct shaped by diverse instructional approaches, contextual factors, and emerging global challenges. While significant progress has been made in understanding how scientific literacy can be developed, gaps remain—particularly in early childhood education and in the integration of cultural and contextual dimensions. Addressing these gaps is essential for creating inclusive and sustainable models of science education that support lifelong learning.

**Methodology:**

This study employed a systematic review design guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to ensure transparency, rigor, and replicability in the research process. A comprehensive literature search was conducted across three major academic databases—EBSCOhost (Education), ERIC, and Web of Science—to capture a wide range of studies related to scientific literacy across formal education levels. The search strategy utilized a combination of key terms, including "scientific literacy," "early childhood education," "primary school," and "higher education," allowing for the inclusion of studies spanning early years through tertiary education contexts.

The selection of studies was governed by clearly defined inclusion and exclusion criteria. Articles were included if they were published between 2001 and 2022, appeared in peer-reviewed journals, and were written in English. Furthermore, only empirical studies that utilized primary data were considered, while conceptual papers, theoretical discussions, and document analyses were excluded to maintain a focus on evidence-based findings.

Studies were also required to explicitly address scientific literacy within formal education settings, including early childhood, primary, secondary, or higher education. This ensured that the review remained aligned with its objective of examining how scientific literacy is constructed across different educational stages.

Following the screening process, the selected articles were systematically organized and coded using a structured spreadsheet. Key information extracted from each study included bibliographic details, research methodology, participant characteristics, and principal findings. A narrative synthesis approach was employed to analyze the data, enabling the identification of recurring patterns, methodological trends, and thematic categories across diverse study designs. This approach allowed for a comprehensive interpretation of the literature while accommodating variations in research methods and contexts.

**Findings and Discussion:**

**1. Effect of Programs/Projects: project-based learning, STEM integration, or digital science notebooks:**
Project-based and problem-based learning approaches, in particular, have been widely recognized for their effectiveness in fostering scientific literacy. These models engage learners in authentic problem-solving tasks, encouraging inquiry, collaboration, and critical thinking. Meta-analytical evidence suggests that problem-based learning significantly enhances students' scientific literacy by promoting deeper conceptual understanding and transferable skills (Ali, L. U. & Indrowati, M.). Similarly, interventions targeting scientific reasoning and attitudes have been shown to improve both cognitive and affective dimensions of literacy (Lieskovský, J. & Sunyík, V., 2022).

In recent years, technology-enhanced learning environments have emerged as powerful tools for advancing scientific literacy. Innovations such as virtual laboratories, game-based learning, and augmented reality provide interactive and immersive experiences that support conceptual understanding. For instance, virtual lab–based guided inquiry has been found to significantly improve students' scientific literacy by enabling them to experiment in simulated environments (Faresta, R. A. et al., 2023). Furthermore, the integration of hybrid artificial intelligence and augmented reality systems presents promising opportunities, although challenges related to accessibility and implementation remain (Wibowo, F. C. et al., 2026).

Contextualization has also been identified as a key factor in the success of instructional interventions. Studies emphasize that connecting scientific concepts to learners' local environments and lived experiences enhances engagement and comprehension. In the Philippine context, meta-analytic findings reveal that contextualized science instruction significantly improves scientific literacy outcomes by making learning more relevant and meaningful (Marchee, T. & Joje Mar, P., 2022). This highlights the importance of culturally responsive pedagogy in science education.

Closely related to contextualization is the integration of ethnoscience, which incorporates indigenous knowledge systems and cultural practices into science learning. Research indicates that ethnoscience-based approaches not only enhance conceptual understanding but also promote cultural identity and inclusivity. A systematic review by Hikmah, N. et al. (2025) underscores the potential of ethnoscience to bridge the gap between formal scientific knowledge and students' everyday experiences, thereby fostering more holistic scientific literacy.

Interdisciplinary approaches further contribute to the development of scientific literacy by connecting science with other domains of knowledge. For example, the integration of energy literacy into science education broadens students' understanding of sustainability and global challenges (Majid, N. A. M. N. A. et al., 2025). Similarly, biological literacy and domain-specific literacies highlight the importance of tailoring instructional strategies to specific scientific disciplines while maintaining coherence across the curriculum (Semilarski, H. & Laius, A., 2021).

Another emerging trend in intervention-based research is the emphasis on multimodal and alternative forms of science communication. Data sonification, for instance, has been shown to help overcome barriers related to numeracy and visualization by translating data into auditory formats (Sawe, N. et al., 2020). Such innovative approaches expand the ways in which learners engage with scientific information, making science more accessible to diverse populations.

Despite the demonstrated effectiveness of these interventions, several studies highlight ongoing challenges in their implementation. Issues such as limited teacher training, inadequate resources, and curriculum constraints hinder the widespread adoption of innovative instructional models. Reviews of learning model development emphasize that while numerous approaches exist, their scalability and sustainability remain key concerns (Habsari, A. F. et al., 2026). This suggests a need for systemic support to ensure that effective interventions can be consistently applied across different educational contexts.

Moreover, the conceptualization and measurement of scientific literacy within intervention studies vary significantly, posing challenges for comparison and generalization. Efforts to develop standardized assessment tools, particularly at the middle school level, highlight the complexity of capturing the multifaceted nature of scientific literacy (Fives, H. et al., 2014). Broader discussions on literacy across domains also suggest that insights from fields such as health and media literacy can inform more comprehensive approaches to scientific literacy assessment (Frisch, A. L. et al., 2012).

The literature underscores the importance of viewing scientific literacy within a broader educational and societal context. Foundational perspectives emphasize that scientific thinking begins in early childhood and develops through sustained engagement with inquiry-based experiences (Lehrer, R. & Schauble, L., 2006). At the same time, global perspectives highlight the critical role of science education in addressing societal challenges and promoting development (Webb, P., 2010). Together, these insights reinforce the need for integrated, context-sensitive, and forward-looking interventions to advance scientific literacy across all levels of education.

**2. Teaching and Learning Practices: Research explored the effectiveness of various instructional models and strategies in the classroom.**

Research on teaching and learning practices has consistently emphasized the critical role of instructional models and classroom strategies in shaping students' scientific literacy. Rather than relying on traditional lecture-based approaches, contemporary science education advocates for learner-centered pedagogies that actively engage students in inquiry, problem-solving, and knowledge construction. These approaches align with broader educational reforms aimed at equipping learners with the competencies required to navigate complex scientific and societal challenges.

A significant body of literature highlights the effectiveness of innovative learning models designed specifically to enhance scientific literacy. Systematic reviews indicate that inquiry-based, problem-based, and project-based learning models are among the most widely implemented strategies in science classrooms (Romli, S. et al., 2024). These models promote active participation and encourage students to explore scientific concepts through investigation and real-world application, thereby fostering deeper understanding and retention.

Among these approaches, project-based learning (PBL) has gained considerable attention for its ability to integrate content knowledge with critical thinking and collaboration skills. Research demonstrates that PBL is particularly effective in promoting scientific literacy across different educational levels, including early childhood settings, where hands-on and experiential learning are essential (Eliza, D. et al., 2025). Such findings reinforce the importance of designing learning environments that support inquiry and exploration from an early age.

In addition to pedagogical models, the integration of technology in teaching practices has emerged as a key factor in enhancing scientific literacy. Interactive multimedia, digital simulations, and STEM-based learning tools have been shown to improve students' engagement and conceptual understanding (Hodaifah, H. et al., 2025; Siahaan, S. M., 2025). These technologies provide dynamic and interactive learning experiences that enable students to visualize complex scientific phenomena and engage with content in more meaningful ways.

The influence of digital culture on science education further underscores the evolving nature of teaching practices. Studies suggest that the integration of digital tools is not only a matter of access but also of cultivating a digital school culture that supports innovation and collaboration (Litina, S. & Rubene, Z., 2024). This highlights the need for schools to adopt holistic approaches that integrate technology into both pedagogy and institutional practices.

Another important dimension of teaching and learning practices is the integration of literacy within science instruction. Research has shown that language skills and scientific understanding are deeply interconnected, with each reinforcing the other. Effective science teaching involves not only the transmission of knowledge but also the development of students' ability to read, write, and communicate scientific ideas (Pearson, P. D. et al., 2010). Similarly, the use of children's literature has been identified as a powerful strategy for promoting both language and scientific literacy, particularly in early education (Heryani, R. et al., 2024).

Emerging interdisciplinary approaches, such as ethno-STEM, further expand the scope of teaching practices by integrating cultural knowledge with scientific concepts. These approaches recognize the value of contextualizing science learning within students' cultural backgrounds, thereby enhancing relevance and engagement (Primadianningsih, C. et al., 2023). Such practices contribute to more inclusive and culturally responsive science education.

Despite the promising impact of these instructional strategies, several challenges remain in their implementation. Reviews have identified issues such as insufficient teacher training, limited resources, and rigid curricula as barriers to the effective integration of scientific literacy-oriented practices (Sukiastini, I. G. A. N. K. et al., 2025). These challenges highlight the need for systemic support and professional development to enable educators to adopt innovative teaching approaches.

Theoretical perspectives also play a crucial role in shaping teaching practices. A Bildung-oriented approach, for instance, emphasizes the development of the whole ব্যক্তি, including ethical, cultural, and intellectual dimensions of learning (Kilag, O. K. et al., 2023). Similarly, alternative frameworks such as Vision III advocate for science education that integrates socio-political and ethical considerations, thereby expanding the goals of scientific literacy beyond technical competence (Sjöström, J., 2025).

Furthermore, the concept of scientific literacy is increasingly being linked to broader forms of literacy, including computational, media, and community literacy. Research indicates that computational literacy is becoming essential in modern science education, enabling students to engage with data and digital tools effectively (Braun, D. & Huwer, J., 2022). Similarly, media literacy is crucial for navigating scientific information in digital environments (Rosenthal, S., 2020), while community scientific literacy emphasizes collective understanding and participation in science-related issues (Busch, K. C. & Rajwade, A., 2024).

This demonstrates that effective teaching and learning practices for scientific literacy require a multifaceted approach that integrates innovative pedagogies, technological tools, interdisciplinary perspectives, and supportive institutional frameworks. While significant progress has been made in identifying effective strategies, the successful implementation of these practices depends on addressing systemic challenges and aligning instructional approaches with broader educational goals. These findings underscore the importance of continuous innovation and contextual adaptation in science teaching to ensure the development of scientifically literate learners.

**Assessing Literacy Levels: Several studies focused solely on measuring the current scientific literacy of students and teachers.**

A significant portion of the reviewed studies focused on assessing the current levels of scientific literacy among students and teachers. These studies primarily aimed to measure learners' understanding of scientific concepts, their ability to apply knowledge in real-life contexts, and their capacity to engage with socio-scientific issues. Assessment-driven research plays a crucial role in identifying existing competencies and gaps, thereby informing instructional design and educational policy.

Most assessment studies relied heavily on quantitative methods, particularly standardized tests, surveys, and structured questionnaires. These instruments were designed to evaluate cognitive domains such as conceptual understanding, reasoning skills, and problem-solving abilities. While such approaches provide measurable and comparable data, they often reduce scientific literacy to discrete skills, overlooking its broader, multidimensional nature (Li, Y. & Guo, M., 2021).

A key trend in the literature is the alignment of assessment tools with internationally recognized frameworks of scientific literacy. Early initiatives, such as those highlighted by Koppal, M. and Caldwell, A. (2004), emphasized the need for coherent standards in science education. These efforts laid the groundwork for subsequent research aimed at developing reliable and valid measures of scientific literacy across different educational levels.

Despite these advancements, scholars have raised concerns regarding the limitations of traditional assessment approaches. Many studies focus primarily on content knowledge and fail to capture essential components such as argumentation, communication, and critical thinking. Research by Cavagnetto, A. R. (2010) highlights the importance of assessing students' ability to construct and evaluate scientific arguments, which is often neglected in standardized testing environments.

Furthermore, the relationship between scientific literacy and higher-order thinking skills has been widely explored. Studies indicate that scientific literacy is closely linked to critical thinking, problem-solving, and reasoning abilities. A scoping review by Bramastia, B. and Rahayu, S. (2023) found that learners with higher levels of scientific literacy demonstrate stronger analytical and evaluative skills, reinforcing the need for assessment tools that go beyond factual recall.

Another important consideration in assessing scientific literacy is the role of socio-scientific issues (SSI). Integrating SSI into assessment frameworks allows for the evaluation of students' ability to apply scientific knowledge in real-world contexts. According to Kumar, V. et al. (2024), SSI-based assessments provide a more authentic measure of scientific literacy by capturing learners' reasoning, decision-making, and ethical considerations.

In addition to cognitive dimensions, recent literature emphasizes the importance of assessing affective and contextual factors. Students' attitudes toward science, motivation, and engagement significantly influence their scientific literacy development. Classroom-based studies suggest that assessment practices should account for these variables to provide a more holistic understanding of learners' capabilities (Yanto, N. & Sari, N. I., 2025).

The integration of interdisciplinary literacies further complicates the assessment of scientific literacy. For instance, climate literacy and environmental awareness require the evaluation of students' understanding of complex, global issues (Azevedo, J. & Marques, M., 2017). Similarly, computational literacy and media literacy demand new forms of assessment that capture learners' ability to interpret and analyze digital information (Braun, D. & Huwer, J., 2022; Rosenthal, S., 2020).

Technological advancements have also influenced assessment practices in science education. Interactive multimedia and digital assessment tools offer new opportunities to evaluate students' understanding in dynamic and engaging ways. Studies indicate that technology-enhanced assessments can provide immediate feedback and support deeper learning (Hodaifah, H. et al., 2025). However, issues related to accessibility and digital equity remain significant challenges.

Despite the growing diversity of assessment approaches, inconsistencies in measurement frameworks persist across studies. Reviews of learning models and scientific literacy research reveal a lack of standardized definitions and instruments, making it difficult to compare findings and draw general conclusions (Romli, S. et al., 2024; Saputra, W. T. et al., 2024). This highlights the need for more unified and theoretically grounded assessment frameworks.

Moreover, systemic challenges continue to hinder the effective assessment of scientific literacy. Factors such as limited teacher training, insufficient resources, and rigid curricular structures restrict the implementation of comprehensive assessment practices (Sukiastini, I. G. A. N. K. et al., 2025). These constraints underscore the importance of aligning assessment strategies with broader educational reforms.

Emerging perspectives advocate for more holistic and humanistic approaches to assessing scientific literacy. A Bildung-oriented framework, for example, emphasizes the development of learners' values, identity, and ethical reasoning alongside cognitive skills (Kilag, O. K. et al., 2023). Similarly, Vision III of scientific literacy calls for assessment practices that incorporate socio-political and ethical dimensions, reflecting the complex realities of modern science (Sjöström, J., 2025).

Finally, recent research highlights the importance of extending assessment beyond individual learners to include community and societal dimensions. The concept of community scientific literacy emphasizes collective

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understanding and participation in science-related issues (Busch, K. C. & Rajwade, A., 2024). This broader perspective challenges traditional assessment models and calls for more inclusive and context-sensitive approaches.

While significant efforts have been made to assess scientific literacy, existing approaches remain largely fragmented and heavily reliant on quantitative measures. Future research should prioritize the development of comprehensive, multidimensional assessment frameworks that capture cognitive, affective, and socio-cultural dimensions of scientific literacy. Such advancements are essential for supporting meaningful learning and ensuring that assessment practices align with the evolving goals of science education.

**4. External Factors: Studies established correlations between scientific literacy and factors such as causal reasoning, executive function, and parental education levels.**

Research on scientific literacy has increasingly highlighted the influence of external factors that extend beyond classroom instruction. These factors include cognitive abilities such as causal reasoning and executive function, as well as socio-environmental variables like parental education, cultural background, and access to learning resources. Together, these elements shape how learners acquire, process, and apply scientific knowledge, underscoring the complexity of scientific literacy as a multidimensional construct.

Cognitive factors play a foundational role in the development of scientific literacy. Studies suggest that skills such as reasoning, problem-solving, and executive functioning are strongly associated with students' ability to understand and apply scientific concepts. Early cognitive development, particularly in terms of scientific thinking and inquiry, has been identified as a critical determinant of later scientific literacy outcomes (Lehrer, R. & Schauble, L., 2006). These findings highlight the importance of nurturing cognitive skills from an early age.

In addition to cognitive dimensions, socio-economic and familial factors significantly influence scientific literacy. Parental education levels, home learning environments, and access to educational resources contribute to disparities in students' scientific understanding. Broader analyses emphasize that science education outcomes are closely tied to social and economic conditions, particularly in developing contexts (Webb, P., 2010). This suggests that improving scientific literacy requires not only pedagogical interventions but also systemic support.

The role of literacy itself as an external factor cannot be overlooked. Research indicates that language proficiency and general literacy skills are deeply interconnected with scientific literacy, as learners must be able to read, interpret, and communicate scientific information effectively (Pearson, P. D. et al., 2010). Similarly, insights from other literacy domains, such as health literacy, provide valuable perspectives on how individuals process complex information and make informed decisions (Frisch, A. L. et al., 2012).

Cultural context also plays a crucial role in shaping scientific literacy. Approaches such as ethno-STEM and ethnoscience emphasize the integration of indigenous knowledge systems and cultural practices into science education. These approaches have been shown to enhance students' engagement and relevance of learning by connecting scientific concepts to their lived experiences (Primadianningsih, C. et al., 2023; Hikmah, N. et al., 2025). Such findings highlight the importance of culturally responsive teaching in promoting inclusive scientific literacy.

Technological factors have also emerged as significant contributors to scientific literacy development. The use of STEM-based learning media, digital tools, and virtual laboratories has been associated with improved engagement and understanding (Siahaan, S. M., 2025; Faresta, R. A. et al., 2023). Moreover, advanced technologies such as artificial intelligence and augmented reality offer new possibilities for enhancing scientific literacy, although their implementation presents challenges related to accessibility and teacher readiness (Wibowo, F. C. et al., 2026).

The broader digital environment, including school culture and access to technology, further influences scientific literacy outcomes. Studies suggest that a supportive digital school culture fosters collaboration, innovation, and effective use of technological resources (Litina, S. & Rubene, Z., 2024). This indicates that the impact of technology is not limited to tools alone but also depends on institutional practices and attitudes.

Instructional interventions, while often categorized as internal factors, also interact with external conditions. For example, contextualized instruction and culturally relevant pedagogy have been shown to enhance scientific literacy by aligning learning with students' environments and experiences (Marchee, T. & Joje Mar, P., 2022). Similarly, approaches such as problem-based learning and project-based learning are more effective when supported by conducive external conditions, including resources and community involvement (Ali, L. U. & Indrowati, M.; Eliza, D. et al., 2025).

Emerging forms of literacy, such as data literacy and interdisciplinary literacies, further expand the range of external influences. In a data-driven world, the ability to interpret and analyze data has become an essential component of scientific literacy (Lee, M. et al., 2024). Additionally, domain-specific literacies, such as biological literacy, highlight the need for specialized knowledge and skills within different scientific disciplines (Semilarski, H. & Laius, A., 2021).

Communication and accessibility of scientific information also serve as critical external factors. Innovative approaches such as data sonification aim to overcome barriers related to numeracy and visualization, making scientific data more accessible to diverse learners (Sawe, N. et al., 2020). Furthermore, broader conceptions of literacy in science education emphasize the importance of adapting instructional and communication strategies to different learner needs (Stahl, G. et al., 2024).

Despite the growing recognition of these external influences, challenges remain in integrating them effectively into science education. Reviews indicate that gaps persist in aligning technological, cultural, and socio-economic factors with instructional practices, limiting their overall impact (Habsari, A. F. et al., 2026). Additionally, inconsistencies in assessment frameworks make it difficult to fully capture the influence of external variables on scientific literacy outcomes (Fives, H. et al., 2014).

The development of scientific literacy is shaped by a complex interplay of cognitive, socio-cultural, technological, and environmental factors. These external influences highlight the need for holistic and context-sensitive approaches to science education that extend beyond classroom instruction. Addressing these factors is essential for creating equitable and sustainable learning environments that support the development of scientifically literate individuals across diverse contexts.

**Conclusion:**

This systematic review provides a comprehensive synthesis of existing empirical research on scientific literacy across formal education, revealing significant patterns, strengths, and persistent gaps within the field. The findings confirm that the construction of scientific literacy has been largely dominated by quantitative methodologies, with a strong emphasis on measurement, assessment, and intervention outcomes, particularly within secondary and higher education contexts. While these approaches have contributed valuable insights into learners' competencies and the effectiveness of instructional strategies, they also reflect a limited conceptualization of scientific literacy as primarily measurable and skill-based, often overlooking its broader cognitive, सामाजिक, and cultural dimensions.

A critical implication of this review is the evident underrepresentation of early childhood education in scientific literacy research. Despite strong theoretical support for the importance of early experiences in shaping long-term learning trajectories, relatively few studies have explored how scientific literacy develops during the early years. This gap restricts a holistic understanding of how foundational skills such as curiosity, inquiry, and reasoning emerge and evolve over time. Consequently, there is a pressing need for future research to shift its focus toward early childhood contexts, employing methodologies that capture young children's perspectives, experiences, and ways of meaning-making.

Furthermore, the review highlights the need to move beyond traditional, assessment-driven paradigms toward more inclusive and context-sensitive approaches. Scientific literacy should be understood not only as an individual cognitive achievement but also as a socially situated practice influenced by cultural norms, community engagement, and real-world contexts. Addressing this requires integrating diverse perspectives, including those related to parental involvement, policy frameworks, and socio-economic conditions, which have been largely overlooked in existing studies. By doing so, researchers and educators can develop more equitable and culturally responsive models of science education.

The findings also underscore the importance of play-based and inquiry-driven pedagogies in fostering scientific literacy, particularly in early childhood settings. Such approaches align with developmental needs and support the natural ways in which young learners explore and interpret the world. However, the limited empirical evidence in this area suggests that these practices remain underexplored and underutilized. Expanding research in this domain will be essential for bridging the gap between theory and practice and for ensuring continuity in scientific literacy development across educational levels.

In addition, this review points to the necessity of adopting interdisciplinary and forward-looking perspectives in scientific literacy research. Emerging domains such as digital, environmental, and data literacy highlight the evolving nature of science education in the 21st century. As global challenges become increasingly complex, the ability to integrate knowledge across disciplines and apply it in meaningful contexts becomes a crucial component of scientific literacy. Future research should therefore explore how these emerging literacies can be effectively incorporated into educational practices from the earliest stages of learning.

Advancing the field of scientific literacy requires a paradigm shift toward more holistic, inclusive, and developmentally appropriate approaches. By prioritizing early childhood education, amplifying children's voices, and addressing the broader socio-cultural and policy-related factors that influence learning, educators and researchers can better support the continuous development of scientifically literate individuals. Such efforts are essential for preparing future generations to navigate an increasingly complex world and to participate thoughtfully and responsibly in science-related societal issues.

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