

CHEMICAL LITERACY AND STUDENTS' CONCEPTUAL UNDERSTANDING AND EFFECTIVE LEARNING STRATEGIES IN A GLOBAL PERSPECTIVE: A SYSTEMATIC LITERATURE REVIEW

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Article History

Received: 10-04-2026

Revision: 03-05-2026

Accepted: 15-05-2026

Published: 26-05-2026

Abstract. This study aims to analyze chemical literacy and students' conceptual understanding, as well as to identify effective learning strategies from a global perspective. The method employed is a *Systematic Literature Review* (SLR) using the PRISMA approach on scientific articles indexed in Scopus within the period of 2015–2025. Based on the selection process, a total of 11 articles met the inclusion criteria and were analyzed using narrative synthesis and thematic analysis based on three main focuses: the development of chemical literacy, its relationship with conceptual understanding, and instructional approaches. The findings indicate that chemical literacy is a multidimensional construct encompassing knowledge, skills, attitudes, and the ability to apply concepts in real-life contexts, and it has evolved toward critical chemical literacy grounded in global issues. Furthermore, the results reveal that the level of students' chemical literacy remains relatively low across various countries and is closely related to their conceptual understanding of chemistry. Various instructional approaches, such as context-based learning, socio-scientific issues (SSI), STEAM, argumentation, and technology integration, have been proven effective in enhancing both chemical literacy and conceptual understanding. In conclusion, chemical literacy and conceptual understanding are interrelated constructs that should be developed integratively through contextual and innovative learning approaches to address global challenges.

Keywords: Chemical Literacy, Conceptual Understanding in Chemistry, Chemistry Learning, Systematic Literature Review, Global Perspective

Abstrak. Penelitian ini bertujuan untuk menganalisis literasi kimia dan pemahaman konsep siswa serta mengidentifikasi strategi pembelajaran efektif dalam perspektif global. Metode yang digunakan adalah *Systematic Literature Review* (SLR) dengan pendekatan PRISMA terhadap artikel ilmiah terindeks Scopus pada rentang tahun 2015–2025. Dari hasil seleksi, diperoleh 11 artikel yang memenuhi kriteria inklusi dan dianalisis menggunakan teknik sintesis naratif dan analisis tematik berdasarkan tiga fokus utama, yaitu perkembangan literasi kimia, hubungan dengan pemahaman konsep, serta pendekatan pembelajaran. Hasil penelitian menunjukkan bahwa literasi kimia merupakan konstruk multidimensional yang mencakup pengetahuan, keterampilan, sikap, dan aplikasi dalam konteks kehidupan nyata serta berkembang menuju literasi kimia kritis berbasis isu global. Selain itu, ditemukan bahwa tingkat literasi kimia siswa masih relatif rendah di berbagai negara dan memiliki hubungan yang erat dengan pemahaman konsep kimia. Berbagai pendekatan pembelajaran seperti context-based learning, socio-scientific issues, STEAM, argumentasi, dan integrasi teknologi terbukti digunakan dalam meningkatkan literasi kimia dan pemahaman konsep. Kesimpulan penelitian ini menunjukkan bahwa literasi kimia dan pemahaman konsep merupakan dua aspek yang saling terkait dan perlu dikembangkan secara integratif melalui pembelajaran yang kontekstual dan inovatif dalam menghadapi tantangan global.

Kata Kunci: Literasi Kimia, Pemahaman Konsep Kimia, Pembelajaran Kimia, *Systematic Literature Review*, Perspektif Global

How to Cite: Islawati., Rohaeti, E., & Priyambodo, E. (2026). Chemical Literacy and Students' Conceptual Understanding and Effective Learning Strategies in a Global Perspective: A Systematic Literature Review. *PEDAGOGIC: Indonesian Journal of Science Education and Technology*, 6 (3), 561-574. <http://doi.org/10.54373/ijset.v6i3.5317>

INTRODUCTION

Chemical literacy, as an integral component of scientific literacy, has emerged as a central focus in chemistry education across various countries, particularly in responding to the increasingly complex and dynamic challenges of the 21st century. Chemical literacy is not merely defined as the ability to master theoretical chemical concepts; rather, it encompasses the capacity to apply such concepts in everyday life, engage in critical thinking, and make science-based decisions within diverse social and environmental contexts. Previous studies have demonstrated that chemical literacy constitutes a multidimensional construct involving knowledge, skills, attitudes, and the ability to apply scientific understanding in real-world situations.

Empirical evidence indicates that context-based learning plays a significant role in bridging the gap between abstract chemical concepts and students' real-life experiences, thereby enhancing chemical literacy (Cigdemoglu & Geban, 2015). This finding is further supported by Wiyarsi et al., (2020), who reported that contextual learning approaches can improve chemical literacy among vocational students, although the outcomes have not yet reached optimal levels. In addition, the development of chemical literacy has expanded to include scientific argumentation and reasoning skills, as evidenced by Cigdemoglu et al., (2017), who found that argumentation-based learning enhances students' ability to construct evidence-based reasoning. Furthermore, Kohen et al., (2019) emphasized the importance of scientific communication through interactions between students and scientists in fostering more meaningful and contextualized chemical understanding. In a broader perspective, the concept of chemical literacy has evolved into critical chemical literacy, incorporating social, ethical, and environmental dimensions, as proposed by Sjöström et al., (2024).

Despite its significance, numerous studies reveal that students' chemical literacy levels remain relatively low across different educational contexts. For instance, Thummathong & Thathong (2018) reported that engineering students in Thailand achieved an average chemical literacy score of only 43.58%, indicating a substantial gap between theoretical instruction and practical application. Similarly, Stašević et al., (2023) found that secondary school students in Serbia lack adequate mastery of fundamental chemical concepts as a prerequisite for developing chemical literacy. These findings suggest the existence of systemic issues in chemistry education, where learning is often oriented toward rote memorization rather than contextual understanding. Moreover, conceptual understanding has been identified as a key determinant of chemical literacy, as mastery of basic concepts is essential for developing comprehensive scientific literacy (Stašević et al., 2023). This relationship is further reinforced

by Sutiani et al., (2025), who demonstrated a positive correlation between chemical literacy and students' learning outcomes, indicating that improvements in chemical literacy directly contribute to enhanced conceptual understanding.

In response to these challenges, various instructional approaches and innovations have been developed to enhance both chemical literacy and conceptual understanding. Context-based learning, as proposed by Cigdemoglu & Geban (2015) and Wiyarsi et al., (2020), has proven effective in connecting chemical concepts with students' real-life contexts. Additionally, socio-scientific issues (SSI)-based learning has been shown to improve chemical literacy by integrating relevant social issues into classroom instruction (Sutiani et al., 2025; Sulistina & Hasanah, 2024). The implementation of STEAM approaches through dilemma-based stories has also been reported to enhance chemical literacy by promoting contextual and collaborative project-based learning (Rahmawati et al., 2024). Furthermore, the integration of digital technologies, such as augmented reality, contributes significantly to facilitating students' understanding of abstract chemical concepts and increasing learning motivation. In addition, argumentation and scientific communication approaches have been identified as effective strategies for improving critical thinking skills and conceptual understanding.

However, despite the effectiveness of these approaches, existing studies remain largely fragmented and context-specific, thus failing to provide a comprehensive understanding of the most effective learning strategies for improving chemical literacy and conceptual understanding at a global level. Several research gaps can be identified. First, most previous studies focus on local contexts or specific chemistry topics, limiting the generalizability of findings. Second, chemical literacy and conceptual understanding are often examined separately, despite their interdependent nature. Third, there is a lack of comprehensive studies that synthesize various instructional strategies and innovations in an integrated framework. Furthermore, existing research tends to be limited to specific educational levels, such as secondary or higher education, without encompassing a broader educational spectrum.

Based on these considerations, this study aims to analyze chemical literacy and students' conceptual understanding, as well as effective learning strategies from a global perspective using a *Systematic Literature Review* approach. Specifically, this study seeks to (1) identify the characteristics and development of chemical literacy concepts in global chemistry education research; (2) analyze the relationship between chemical literacy and students' conceptual

understanding; and (3) identify the most effective instructional approaches, strategies, and innovations for improving both aspects. This study is expected to contribute to the development of a more comprehensive and contextualized framework of chemical literacy and to provide recommendations for more effective and globally relevant chemistry instruction.

In line with these objectives, the research questions are formulated as follows: (1) What are the characteristics and development of chemical literacy concepts in global chemistry education research? (2) What is the relationship between chemical literacy and students' conceptual understanding as reported in previous studies? and (3) What instructional approaches, strategies, and innovations are most effective in improving chemical literacy and conceptual understanding based on existing research findings? These research questions are designed to provide a comprehensive understanding of chemical literacy within a global context and to identify key factors influencing its development, thereby contributing to the advancement of chemistry education in addressing future global challenges.

METHOD

This study employed a *Systematic Literature Review* (SLR) design aimed at systematically identifying, evaluating, and synthesizing research findings related to chemical literacy, students' conceptual understanding, and effective learning strategies from a global perspective. The SLR approach was selected to ensure that the review process was conducted in a structured, transparent, and replicable manner, thereby enhancing the reliability and validity of the findings.

The scope of this study focused on scientific articles published within the period of 2015–2025. This time frame was deliberately selected to capture the most recent developments in chemical literacy research, particularly following the increasing global emphasis on 21st-century skills, scientific literacy, and sustainability-oriented education. Since approximately 2015, research on chemical literacy has shown significant growth, accompanied by the emergence of more complex frameworks, such as critical chemical literacy, the integration of socio-scientific issues (SSI), and the incorporation of digital technologies in chemistry learning. Therefore, limiting the review to this period ensures the inclusion of contemporary, relevant, and methodologically advanced studies that reflect current trends and challenges in global chemistry education. The inclusion criteria comprised: (1) articles indexed in Scopus tiers Q1, Q2, Q3, and Q4, (2) studies relevant to chemical literacy and conceptual understanding, and (3) articles with full-text availability. Conversely, exclusion criteria

included duplicate articles, studies lacking abstracts, and those not aligned with the research focus, all of which were systematically eliminated following PRISMA procedures.

The subjects of this study consisted of research documents in the form of scientific journal articles, which were analyzed in depth based on their respective research characteristics. The research instrument utilized was a data extraction sheet, developed to systematically capture essential information from each article, including authorship and publication year, research location, methodology, underlying theoretical framework, research findings, and identified limitations. The analyzed literature encompassed key studies published between 2015 and 2025, such as Cigdemoglu & Geban (2015), Cigdemoglu et al., (2017), Kohen et al., (2019), Wiyarsi et al., (2020), Stašević et al., (2023), Sulistina & Hasanah (2024), Rahmawati et al., (2024), Sjöström et al., (2024), Sutiani et al., (2025), and Basheer et al., (2025), which collectively provide a comprehensive overview of chemical literacy within a global context.

The data collection procedure was conducted through several systematic stages, including: (1) identification of relevant literature based on predefined keywords, (2) screening of titles and abstracts, (3) selection of articles aligned with the research objectives, and (4) full-text eligibility assessment. Subsequently, the data were analyzed using thematic analysis and narrative synthesis techniques, whereby the findings were categorized into three primary focuses corresponding to the research questions: (1) the development of chemical literacy, (2) its relationship with conceptual understanding, and (3) the effectiveness of instructional strategies. This analytical approach enabled the identification of patterns, trends, and interrelationships among the studied variables in a systematic manner.

RESULTS

Characteristics and Development of Chemical Literacy in a Global Perspective

The synthesis results indicate that chemical literacy is consistently conceptualized as a multidimensional construct, encompassing knowledge, skills, attitudes, and the ability to apply chemical concepts in real-life contexts. Initially, chemical literacy was primarily defined as the ability to understand chemical concepts and relate them to everyday life through contextual learning approaches (Cigdemoglu & Geban, 2015). Subsequently, the concept evolved to include scientific argumentation, which emphasizes critical thinking and evidence-based reasoning (Cigdemoglu et al., 2017).

Furthermore, chemical literacy has expanded to incorporate scientific communication, particularly through interactions between students and scientists in informal learning contexts (Kohen et al., 2019). In addition, Wiyarsi et al., (2020) emphasized that chemical literacy

should be adapted to specific educational contexts, such as vocational education, which requires alignment with workplace relevance. More recent developments highlight the emergence of critical chemical literacy, which integrates social, ethical, and environmental dimensions within a global framework (Sjöström et al., 2024).

Basheer et al., (2025) emphasized the growing integration of chemical literacy with sustainability and green chemistry, underscoring its role in fostering environmental awareness. In line with this development, Sutiani et al., (2025) categorized chemical literacy into four levels: nominal, functional, conceptual, and multidimensional. These findings indicate that chemical literacy has evolved from basic conceptual understanding into a complex, contextual, and globally oriented construct.

Levels of Chemical Literacy and Students' Conceptual Understanding Across Contexts

The results reveal that the level of chemical literacy among students and university learners remains relatively low and varies across educational contexts. For instance, Thummathong & Thathong (2018) reported that engineering students in Thailand achieved an average chemical literacy score of 43.58%, which falls into the low category. Similarly, Stašević et al., (2023) found that secondary school students in Serbia have not yet mastered fundamental chemical concepts related to everyday life. Although improvements have been observed through innovative instructional approaches, such as contextual learning, the overall level of chemical literacy has not yet reached optimal standards (Wiyarsi et al., 2020). Additionally, Sutiani et al., (2025) identified differences in literacy levels between students exposed to socio-scientific issues (SSI)-based learning and those taught using conventional methods.

These findings are further supported by Cigdemoglu & Geban (2015), who demonstrated that students engaged in contextual learning exhibit higher levels of chemical literacy compared to those receiving traditional instruction. Moreover, Stašević et al., (2023) emphasized that limited conceptual understanding significantly contributes to low levels of chemical literacy. Kohen et al., (2019) also suggested that students' chemical literacy can be reflected in the quality of questions posed during scientific interactions. Thus, the findings indicate that both chemical literacy and conceptual understanding remain key challenges in global chemistry education.

Relationship Between Chemical Literacy and Conceptual Understanding

The results demonstrate a significant and reciprocal relationship between chemical literacy and students' conceptual understanding. Sutiani et al., (2025) reported a positive correlation

between chemical literacy and students' learning outcomes, indicating that higher literacy levels are associated with better conceptual understanding.

Similarly, Cigdemoglu & Geban (2015) found that improvements in chemical literacy through contextual approaches are accompanied by enhanced conceptual understanding. Stašević et al., (2023) further emphasized that mastery of fundamental chemical concepts is a prerequisite for achieving chemical literacy. In addition, Cigdemoglu et al., (2017) demonstrated that argumentation skills, as a component of chemical literacy, contribute to improved conceptual understanding through evidence-based discussions. Kohen et al., (2019) also highlighted the role of scientific interaction in enhancing contextual understanding of chemical concepts. Furthermore, the integration of technology, such as augmented reality, has been shown to facilitate the understanding of abstract chemical concepts (Sulistina & Hasanah, 2024), while STEAM-based project learning promotes simultaneous development of chemical literacy and conceptual understanding (Rahmawati et al., 2024). These findings confirm that chemical literacy and conceptual understanding are interdependent constructs that mutually reinforce each other.

Instructional Approaches and Strategies to Enhance Chemical Literacy

The results identify various instructional approaches that are effective in improving chemical literacy and conceptual understanding. Among these, context-based learning has been widely applied to connect chemical concepts with real-life contexts (Cigdemoglu et al., 2017). Additionally, the socio-scientific issues (SSI) approach has been shown to enhance chemical literacy by integrating relevant social issues into learning processes (Sulistina & Hasanah, 2024; Sutiani et al., 2025). The STEAM-based project approach also contributes to improved literacy through collaborative and contextual learning experiences (Rahmawati et al., 2024). Furthermore, argumentation-based learning has been identified as an effective strategy for enhancing critical thinking and conceptual understanding (Cigdemoglu et al., 2017). The integration of digital technologies, particularly augmented reality, supports students in visualizing abstract chemical concepts more effectively (Sulistina & Hasanah, 2024). In addition, approaches emphasizing scientific communication (Kohen et al., 2020) and green chemistry and sustainability (Basheer et al., 2025) further contribute to the development of chemical literacy in a global context.

Distribution of Research Methods and Contexts

The synthesis indicates that studies on chemical literacy employ diverse research methods, including quantitative, qualitative, mixed methods, and research and development (R&D)

approaches. These studies are conducted across various educational contexts, including secondary schools, vocational institutions, and higher education, as well as across multiple countries such as Thailand, Serbia, Indonesia, Israel, and Turkey.

Trends in Chemical Literacy Research

The findings reveal a significant increase in chemical literacy research publications after 2015, with a peak observed around 2024–2025. This trend reflects the growing recognition of chemical literacy as a critical component of modern chemistry education, particularly in addressing global challenges such as sustainability and technological advancement. Overall, the results demonstrate that chemical literacy has become an increasingly prominent focus in global research, with continuous development in both conceptual frameworks and instructional strategies.

DISCUSSION

Characteristics and Development of Chemical Literacy in a Global Perspective

The findings of this study indicate that chemical literacy has undergone a dynamic evolution from a simple conceptual understanding toward a complex multidimensional construct. This result is consistent with Cigdemoglu & Geban (2015), who conceptualized chemical literacy as the ability to understand chemical concepts and relate them to real-life contexts through contextual learning approaches. In its subsequent development, Cigdemoglu et al., (2017) expanded this concept by incorporating scientific argumentation, emphasizing critical thinking and evidence-based reasoning as integral components of chemical literacy. Furthermore, Kohen et al., (2019) demonstrated that chemical literacy also includes scientific communication, particularly through interactions between students and scientists, thereby extending its scope beyond cognitive aspects into social and communicative domains. This indicates a paradigm shift in which chemical literacy is no longer limited to content mastery but also encompasses complex scientific thinking processes.

More recent developments highlight the emergence of critical chemical literacy, which integrates social, ethical, and environmental dimensions within a global context (Sjöström et al., 2024). This perspective is reinforced by Basheer et al., (2025), who emphasized the role of green chemistry and sustainability in enhancing environmental awareness as part of chemical literacy. In addition, the classification proposed by Sutiani et al., (2025), which categorizes chemical literacy into nominal, functional, conceptual, and multidimensional levels, further confirms the progressive and hierarchical nature of this construct. The significance of these

findings lies in clarifying chemical literacy as a 21st-century competency that extends beyond academic contexts to broader social and global dimensions. This study contributes theoretically by integrating diverse perspectives into a comprehensive framework and emphasizes the urgency of developing critical chemical literacy in response to global challenges such as sustainability and climate change.

The Relationship Between Chemical Literacy and Students' Conceptual Understanding

The results demonstrate a strong and interdependent relationship between chemical literacy and students' conceptual understanding. This finding aligns with Sutiani et al., (2025), who reported a positive correlation between chemical literacy and students' learning outcomes, indicating that higher literacy levels are associated with improved conceptual understanding. Similarly, Cigdemoglu & Geban (2015) found that contextual learning not only enhances chemical literacy but also improves students' understanding of chemical concepts. Moreover, Stašević et al., (2023) emphasized that mastery of fundamental chemical concepts is a prerequisite for achieving chemical literacy, highlighting the foundational role of conceptual understanding. On the other hand, Cigdemoglu et al., (2017) demonstrated that argumentation skills, as part of chemical literacy, can enhance conceptual understanding through evidence-based discussions.

In addition, Kohen et al., (2019) revealed that interaction with scientists can deepen students' conceptual understanding through scientific communication, while Sulistina & Hasanah (2024) showed that augmented reality facilitates the comprehension of abstract concepts through visualization. Furthermore, Rahmawati et al., (2024) demonstrated that STEAM-based project learning enhances both chemical literacy and conceptual understanding simultaneously through contextual and collaborative learning environments. These findings indicate that the relationship between chemical literacy and conceptual understanding is reciprocal and mutually reinforcing, suggesting that both constructs should be developed simultaneously within chemistry learning. This study contributes by integrating these variables into a unified analytical framework, which has often been examined separately in previous research.

Table 1. Synthesis aspects and key findings

No	Synthesis Aspect	Key Findings
1	Characteristics of Chemical Literacy	Chemical literacy is multidimensional (knowledge, skills, attitudes, application)

		Develops from conceptual understanding toward critical literacy (social, ethical, environmental) Includes scientific argumentation and communication Integrated with technology and global issues (sustainability)
2	Level of Chemical Literacy	Tends to be low across countries and educational levels Engineering students: average 43.58% (low category) Students have not mastered basic chemical facts Improvement occurs when innovative learning is implemented
3	Relationship with Conceptual Understanding	Chemical literacy is positively correlated with learning outcomes Conceptual understanding is a prerequisite for chemical literacy The relationship is reciprocal (mutual relationship) Argumentation and discussion improve conceptual understanding
4	Instructional Approaches	Context-Based Learning improves chemical literacy Socio-Scientific Issues (SSI) effectively improve literacy and learning outcomes STEAM-based projects enhance literacy and higher-order thinking skills (HOTS) Argumentation improves critical thinking Technology (AR) helps in understanding abstract concepts Green chemistry and sustainability enhance environmental awareness
5	Research Methods	Quantitative (tests, experiments) Qualitative (case studies, interviews) Mixed methods R&D (development of media/AR)
6	Research Context	Secondary schools, vocational education, and higher education Global context (Thailand, Serbia, Indonesia, Israel, Turkey)
7	Research Trends	Publications increased significantly after 2015 Peak publications around 2024–2025 Focus shifts toward global issues and technology

Effective Learning Approaches, Strategies, and Innovations

The findings reveal that contextual, problem-based, and technology-integrated learning approaches are the most effective strategies for enhancing chemical literacy and conceptual understanding. This result is consistent with Cigdemoglu (2015) and Wiyarsi et al., (2020), who demonstrated that context-based learning improves chemical literacy by linking chemical concepts to real-life situations.

In addition, the socio-scientific issues (SSI) approach has been shown to effectively enhance chemical literacy by integrating relevant social issues into learning processes (Sulistina & Hasanah, 2024; Sutiani et al., 2025). This approach not only improves conceptual

understanding but also develops critical thinking and scientific decision-making skills. Furthermore, STEAM-based project learning promotes chemical literacy through collaborative and contextual activities, while argumentation-based learning enhances critical thinking and conceptual understanding through evidence-based discussions (Cigdemoglu et al., 2017; Rahmawati et al., 2024). The integration of technology also plays a crucial role in modern chemistry education. Sulistina & Hasanah (2024) demonstrated that augmented reality facilitates students' understanding of abstract chemical concepts, while Kohen et al., (2019) highlighted the importance of scientific communication through digital interaction with experts. Additionally, Basheer et al., (2025) emphasized that incorporating sustainability concepts into chemistry learning enhances environmental awareness as part of chemical literacy.

The significance of these findings lies in their contribution to identifying integrated and effective instructional strategies. This study provides practical implications for educators in designing innovative, contextual, and technology-enhanced learning environments that align with students' needs and global educational demands.

Research Implications

This study provides both theoretical and practical implications. Theoretically, it enriches the conceptual framework of chemical literacy by integrating diverse perspectives into a comprehensive model. Practically, it offers recommendations for educators to implement contextual, problem-based, and technology-integrated approaches in chemistry learning. Furthermore, the findings support curriculum development that emphasizes critical chemical literacy and global issues, particularly sustainability and environmental awareness.

CONCLUSION

The findings indicate that chemical literacy is a multidimensional construct that continues to evolve in global chemistry education and is strongly associated with students' conceptual understanding. Beyond mere conceptual mastery, it encompasses critical thinking, scientific communication, and awareness of social and environmental issues, reflecting its role as a comprehensive 21st-century competency. However, students' chemical literacy levels remain relatively low across various educational contexts, highlighting a persistent gap between theoretical knowledge and its application in real-life situations. The relationship between chemical literacy and conceptual understanding is reciprocal, whereby improvements in one dimension contribute to the enhancement of the other. Various instructional approaches,

including context-based learning, socio-scientific issues (SSI), STEAM, argumentation, and technology integration, have been identified as effective in simultaneously strengthening both aspects. This study contributes by synthesizing global research into a comprehensive framework that positions chemical literacy as a holistic and contextual construct within contemporary chemistry education. Nevertheless, several limitations should be acknowledged, including the restriction to Scopus-indexed articles, which may have excluded other relevant studies, the context-specific nature of many reviewed studies that may limit generalizability, and the reliance on literature-based analysis without direct empirical validation. Furthermore, variations in research methodologies among the selected studies pose challenges in achieving a fully consistent synthesis. Therefore, future research is recommended to conduct empirical investigations across diverse educational contexts to further validate and expand the understanding of the relationship between chemical literacy and conceptual understanding.

RECOMMENDATIONS

Future research is recommended to develop empirical studies that directly examine the relationship between chemical literacy and conceptual understanding across diverse educational contexts. Additionally, subsequent studies should involve a broader range of educational levels, from primary education to higher education, to provide a more comprehensive understanding of the development of chemical literacy. Moreover, future research should explore the integration of multiple instructional approaches simultaneously to identify the most effective combination of strategies for enhancing chemical literacy and conceptual understanding. There is also a need to investigate the role of digital technologies, such as augmented reality and scientific communication platforms, in supporting the development of chemical literacy in the digital era. Furthermore, it is essential to examine chemical literacy within the context of global issues, such as sustainability and climate change, to strengthen the relevance of chemistry education in addressing contemporary challenges. In conclusion, future studies are expected to extend and deepen the findings of this research, thereby contributing more broadly to the advancement of chemistry education at a global level.

ACKNOWLEDGMENTS

The authors would like to express their sincere gratitude to all individuals and institutions who have contributed to the completion of this study. Special appreciation is extended to the academic advisors for their invaluable guidance, constructive feedback, and continuous support throughout the research process. The authors also acknowledge the financial support provided

by the relevant institutions, which has significantly facilitated the implementation of this research. In addition, appreciation is directed to colleagues and reviewers who have provided insightful comments and suggestions that improved the quality of this manuscript. Furthermore, the authors would like to thank all contributors who assisted in data collection, proofreading, and technical preparation of the manuscript. Their contributions have been essential in ensuring the successful completion of this study.

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