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# Strengthening Digital Literacy in the Teaching and Learning of Chemistry: A Literature Review

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**Abstrak**

Penelitian ini bertujuan untuk menganalisis strategi penguatan literasi digital dalam pembelajaran kimia melalui kajian literatur. Literasi digital menjadi kompetensi esensial abad ke-21 yang tidak hanya mencakup keterampilan teknis, tetapi juga kapasitas kognitif, sosial, dan pedagogis dalam memanfaatkan teknologi secara kritis dan bertanggung jawab. Metode penelitian menggunakan *systematic literature review* dengan menelaah 50 artikel dari basis data jurnal *open access* yang berasal dari kombinasi jurnal nasional (seperti JKPK, JPI, JPSI, IJERR) dan jurnal internasional open access (misalnya *Journal of Chemical Education, J. Phys. Conf. Ser., iJET, Education and Information Technologies*) yang kemudian direduksi menjadi 20 artikel dan dipilih 15 artikel paling relevan berdasarkan kriteria inklusi. Artikel yang dianalisis dipublikasikan dalam rentang waktu 2020–2024, berfokus pada strategi pembelajaran kimia berbasis digital, dan berasal dari jurnal open access untuk menjamin transparansi dan aksesibilitas. Hasil kajian menunjukkan bahwa sebagian besar siswa maupun calon guru kimia awalnya memiliki tingkat literasi digital sedang, namun strategi pembelajaran berbasis teknologi terbukti mampu meningkatkan kompetensi tersebut secara signifikan. Strategi yang paling sering digunakan meliputi penggunaan e-modul berbasis Android, media *Augmented Reality* (AR), laboratorium virtual, pembelajaran berbasis proyek (STEAM-PjBL), serta integrasi perangkat lunak kimia seperti *ChemDraw*. Temuan ini menegaskan bahwa keberhasilan penguatan literasi digital tidak hanya ditentukan oleh ketersediaan teknologi, tetapi juga oleh keselarasan pedagogis, kesiapan guru, dan keterlibatan aktif siswa. Oleh karena itu, literasi digital perlu diposisikan sebagai kompetensi inti dalam pembelajaran kimia untuk memastikan pengalaman belajar yang bermakna, setara, dan berorientasi masa depan.

Kata Kunci: AR, e-modul, literasi digital, pembelajaran kimia, project-based learning

**Abstract**

*This study aims to analyze strategies for strengthening digital literacy in chemistry education through a systematic literature review. Digital literacy is recognized as an essential 21st-century competence that encompasses not only technical skills but also cognitive, social, and pedagogical capacities to use technology critically and responsibly. The research employed a systematic literature review method, initially identifying 50 open access journal articles, which were then reduced to 20 and finally narrowed down to 15 articles based on inclusion criteria. The selected studies, published between 2020 and 2024, specifically addressed digital literacy strategies in chemistry education and were drawn exclusively from open access journals to ensure transparency and accessibility. The results indicate that most students and pre-service chemistry teachers initially demonstrated moderate levels of digital literacy, yet structured technology-based interventions significantly improved these competencies. The most frequently reported strategies included Android-based e-modules, Augmented/Virtual Reality (AR/VR) media, virtual laboratories, STEAM project-based learning, and the integration of chemistry software such as ChemDraw. These findings highlight that the success of digital literacy development depends not only on the availability of digital tools but also on pedagogical alignment, teacher preparedness, and active student engagement. Consequently, digital* *literacy should be regarded as a core competency in chemistry education to ensure equitable, meaningful, and future-oriented learning experiences.*

*Keywords: AR, chemistry education, digital literacy, e-modules, project-based learning*

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## Introduction

In the era of the Fourth Industrial Revolution, digital literacy has emerged as one of the essential competencies for students and educators alike. The rapid advancement of information and communication technologies (ICT) has fundamentally transformed educational practices across various disciplines, including the teaching and learning of chemistry. The integration of digital tools significantly aids in visualization, experimentation, and collaboration in chemistry education (Quraishi et al., 2024). However, while technology is widely available, the development of digital literacy skills—defined as the ability to effectively, critically, and responsibly use digital resources—remains uneven between teachers and learners (Dewi, 2021). This gap highlights the urgent need for strategies aimed at strengthening digital literacy in chemistry education to ensure that technological integration enhances learning outcomes (Sinaga et al., 2024). Digital literacy is recognized not only as a technical skill but also encompasses cognitive and socio-cultural competencies, leading to empowerment and enhanced engagement in educational practices (Repanovici et al., 2024). The effectiveness of digital literacy in improving educational outcomes is supported by studies indicating that well-structured and integrated digital literacy training can significantly impact students' success and engagement (Marín & Castañeda, 2022; Salisbury et al., 2024). As education increasingly relies on technology, it is imperative that both educators and students develop robust digital literacy skills to navigate the complexities of modern learning environments effectively. This emphasis on strengthening digital competencies is crucial for preparing students for future challenges and opportunities in the digital world (Holm, 2024; Mulyani et al., 2023). Furthermore, research indicates that the application of digital literacy in chemistry is vital as it enables students to navigate complex representations and engage in critical analysis of information resources (Quraishi et al., 2024). The urgency of this issue lies in the growing recognition that digital literacy is not merely a technical skill but also a cognitive and socio-cultural competence (Nikou & Aavakare, 2021). In chemistry education, students are expected to engage with complex representations such as molecular models and chemical equations. Digital platforms provide innovative ways to represent these abstract concepts; however, without adequate digital literacy, learners may misuse, misunderstand, or fail to critically evaluate the information provided (Berber et al., 2023). For teachers, digital literacy also encompasses the pedagogical capacity to design, implement, and assess learning activities that leverage technology in meaningful ways (Butar et al., 2024). Consequently, the success of digital transformation in chemistry education depends not only on access to technology but also on deliberate strategies that foster digital literacy for both teachers and students (Kurniasih, 2023). These strategies should include professional development and educational resources that target the integration of digital tools in pedagogical methods, emphasizing the importance of fostering creative and critical thinking skills through technology (Yontar, 2019). This multifaceted approach to digital literacy empowers both students and educators, fostering an enhanced learning environment in chemistry education.

Recent research trends demonstrate an increasing interest in exploring how digital literacy can be cultivated in science education through various approaches such as virtual laboratories, gamification, digital simulations, and collaborative online learning environments (Nikou & Aavakare, 2021). In chemistry, virtual and augmented reality applications and interactive learning platforms have been widely utilized to help students visualize microscopic processes and practice experimental procedures in a safe and cost-effective manner (Kornienko & Mishina, 2023; Oliynyk et al., 2024). Yet, literature also indicates that despite the proliferation of digital tools, the effective use of these resources requires more than technical familiarity; it necessitates critical thinking, creativity, and the ability to evaluate the credibility of digital content (Hamsiah et al., 2024). Therefore, a literature review is needed to map out the strategies that have been proposed and tested in previous studies to strengthen digital literacy in the teaching and learning of chemistry. Previous research highlights the efficacy of blended learning models and interactive platforms as effective frameworks for enhancing digital literacy competencies among students (Kiryakova & Kozhuharova, 2024; Srivastava & Dangwal, 2021). The need for empirical studies to evaluate these strategies and their resultant impacts on student engagement and understanding is also reinforced (Braslauskienė et al., 2024).

Strengthening digital literacy in chemistry education aligns with the broader goals of 21st-century education, which emphasize the development of critical thinking, collaboration, communication, and creativity (Pangrazio et al., 2020). By integrating digital literacy into chemistry learning, educators can enhance students' conceptual understanding and prepare them to thrive in digital and knowledge-based societies, as digital skills are crucial for functioning effectively in modern contexts (Nikou et al., 2022). Such integration also addresses issues of equity and access, ensuring students from diverse backgrounds are empowered to engage meaningfully with scientific knowledge in digital contexts (Çetinkaya, 2024). Strategies to strengthen digital literacy extend beyond individual skill development to encompass institutional policies, teacher training programs, and curriculum design that prioritize digital competence as a core educational outcome (Aini, 2023). Comprehensive approaches are necessary to create inclusive learning environments that leverage digital technologies to facilitate equitable access to educational resources (Kardeş, 2020). To achieve this, educational frameworks must focus not only on improving technical skills but also on fostering an environment where learners can critically analyze and creatively engage with digital content, thus preparing them for the demands of future workplaces and society (Maya & Suseno, 2022).

Given these considerations, this article aims to conduct a literature review on strategies for strengthening digital literacy in the teaching and learning of chemistry. By analyzing previous research and identifying recurring themes, practices, and challenges, this review seeks to provide a comprehensive understanding of how digital literacy has been addressed in chemistry education. The ultimate goal is to highlight effective approaches, uncover gaps in the existing literature, and suggest directions for future research and practice. In doing so, this review underscores the critical role of digital literacy in ensuring that technological innovations in chemistry education translate into meaningful, equitable, and sustainable learning experiences for both teachers and students. The framing of digital literacy as a dynamic and evolving set of competencies underscores the necessity for ongoing research and adaptive pedagogies that meet the demands of contemporary educational contexts (Arissaputra et al., 2023; Quraishi et al., 2024). Emphasizing this fluidity in competencies will enhance the adaptability of both students and educators to the challenges posed by rapidly advancing digital landscapes (Listiawati et al., 2022). Studies have also suggested that integrating digital literacy into teaching practices is crucial for creating engaging learning experiences that foster critical thinking and creativity among students (Hebebci et al., 2020). Ultimately, the significance of this research lies in its potential to inform curriculum design, teacher professional development, and policy-making efforts aimed at embedding digital literacy as a core competency in chemistry education.

## Method

This study employed a systematic literature review approach to analyze strategies for strengthening digital literacy in the teaching and learning of chemistry. The review process was conducted in several stages following standard screening and eligibility procedures. The initial stage involved the identification of relevant articles through searches in several open access journal databases, including the Directory of Open Access Journals (DOAJ), ERIC, Springer Open, Taylor & Francis Online (open access articles), and Indonesian indexed journals such as JKPK (Jurnal Kimia dan Pendidikan Kimia), JPI (Jurnal Pendidikan IPA), and Indonesian Journal of Educational Research and Review (IJERR). The decision to limit the sources to open access journals was made to ensure transparency, accessibility, and verifiability of all the research materials used. This stage yielded a total of 50 articles.

The screening stage reduced the number of articles to 20, based on their alignment with the research theme and publication year. Studies that did not explicitly address digital literacy, chemistry education, or were published before 2020 were excluded.

In the eligibility stage, further inclusion criteria were applied to ensure methodological rigor and relevance.

Table 1. Eligibility Criteria and Exclusion Reasons

| Criteria | Inclusion | Exclusion Reasons |
|---|---|---|
| Topic Focus | Articles addressing digital literacy strategies, models, or media in education, specifically related to chemistry or science with strong applicability to chemistry. | Articles focusing on general digital literacy unrelated to education; studies in non-science domains (e.g., economics, humanities). |
| Discipline | Chemistry education or broader science education contexts where findings are directly transferable to chemistry learning. | Studies limited to biology, physics, or ICT without clear chemistry integration. |
| Publication Period | Articles published between 2020–2024, ensuring relevance to current educational and technological contexts. | Articles published before 2020, deemed outdated in relation to rapid digital transformation in education. |
| Accessibility | Open access journals to ensure transparency and verifiability. | Articles behind paywalls or restricted access. |
| Research Quality | Peer-reviewed journal articles with clear methodology and findings. | Conference abstracts, opinion pieces, or non-peer-reviewed sources. |

After applying these criteria, a final set of 15 articles was included for full review and analysis. These articles were then synthesized to identify patterns in digital literacy profiles, instructional strategies, and the effectiveness of digital tools in chemistry learning.

The following diagram is the PRISMA flow diagram illustrating the selection process:

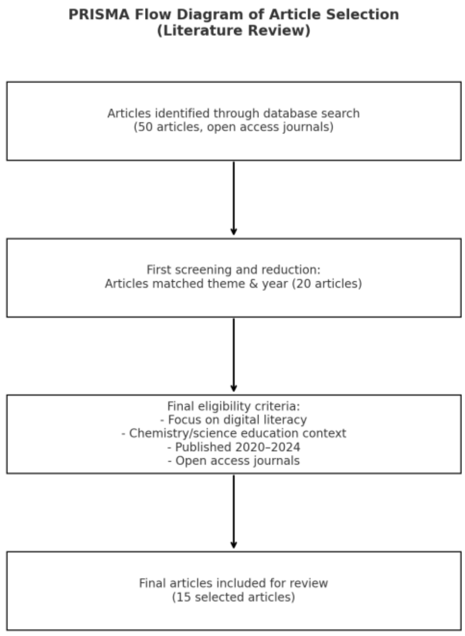



Figure 1. PRISMA Flow Diagram Showing the Selection Process of Articles Included in the Review

**Results and Discussion**

The present study was conducted using a systematic literature review approach to examine strategies for strengthening digital literacy in chemistry education. A total of 50 articles were initially identified from open access databases and reputable journals, which were then reduced to 20 articles after a first stage of screening. Applying stricter inclusion criteria—such as relevance to chemistry education, focus on digital literacy, publication period between 2020 and 2024, and availability in open access format—led to a final selection of 15 articles. These articles were synthesized and analyzed to generate comprehensive insights into the current state of research, focusing on profiles of digital literacy, instructional strategies, and the effectiveness of digital media tools in fostering digital competencies in chemistry learning. This process ensured that the findings presented in this study are grounded in recent, accessible, and contextually relevant scholarship.

The purpose of this research is to map the strategies that have been tested and implemented in previous studies while highlighting the critical importance of digital literacy as a core competency in chemistry education (Abd Majid & Majid, 2018; Mazzuco et al., 2022). In the context of the Fourth Industrial Revolution and the rapid expansion of digital technologies in education, strengthening digital literacy is essential for enabling students to critically navigate complex chemical concepts, engage meaningfully with digital content, and develop transferable skills needed for lifelong learning (Badilla Quintana et al., 2020). By presenting a synthesis of diverse strategies—including augmented reality (AR) applications, virtual laboratories, and project-based approaches—this review emphasizes both the progress that has been achieved and the challenges that remain (Arief et al., 2018; Shan Wong et al., 2021). The significance of this study lies in its contribution to advancing chemistry education practices, informing teacher professional development, and guiding future research directions that seek to promote equitable and sustainable integration of digital literacy in science learning. (Thu Hoài et al., 2024; Yawan, 2022).

This section presents the results of the systematic literature review, which analyzed 15 selected articles on strategies for strengthening digital literacy in the teaching and learning of chemistry. The findings are organized into three main categories: (1) the overall mapping of selected studies, (2) the profile and level of digital literacy among students and pre-service teachers, and (3) the instructional strategies and digital media used to enhance digital literacy in chemistry education.

The literature matrix presented in Table 1 provides a comprehensive overview of research conducted on digital tools and media in chemistry education. A notable trend arises with a significant number of studies utilizing survey or quasi-experimental methods, suggesting a commitment to empirical validation. This methodology underscores the importance of assessing the effectiveness of innovative digital media, which has been shown to enhance students' digital literacy and engagement. For instance, integrating gamified tools has been reported to improve students' understanding of complex chemistry concepts (Clapson et al., 2020; Rizvan et al., 2023). The introduction of interactive technologies, such as augmented reality (AR), supports personalized learning experiences, facilitating a deeper comprehension of scientific principles in an engaging manner (Abdinejad et al., 2021; Badilla Quintana et al., 2020).

Moreover, the studies reflect a convergence of digital innovation and pedagogical advancement aimed at fostering student-centered learning environments. For example, the implementation of digital escape rooms has been demonstrated to enhance active learning, engaging students in problem-solving related to chemistry while promoting teamwork and critical thinking (Abdul Rahim & Chuah, 2024; Lathwesen & Eilks, 2024). Similarly, gamified approaches have shown potential in bridging the gap between pre-college and undergraduate education, illustrating the versatility of digital tools in fostering an interactive learning atmosphere. Such initiatives align with the overarching goal of integrating digital skills into the chemistry curriculum, ensuring that students are well-equipped to navigate the complexities of modern scientific inquiry (Elías et al., 2022). Continued exploration into these digital methodologies is crucial for leveraging technology to enhance educational outcomes in chemistry across diverse learning contexts.

Table 2. Literature Matrix of Selected Articles

| Author(s) | Year | Method | Key Findings | Relevance |
|---|---|---|---|---|
| Enawaty et al. | 2025 | R&D (digital game cards) | Improved hydrocarbon understanding & digital literacy | High |
| Latip & Sutantri | 2021 | Survey (distance learning) | Students' digital literacy mostly moderate | Medium |
| Nadiyyah | 2024 | Descriptive | Software Diamond enhanced | High |

| | | | | |
|---|---|---|---|---|
| et al. | | (crystal visualization) | literacy & visualization | |
| Yulianti et al. | 2022 | Survey (922 students) | Digital literacy average; AR media needed | High |
| Dewi et al. | 2021 | Qualitative (Gen Z chemistry students) | Urgency of digital literacy in chemistry learning | High |
| Dewi et al. | 2022 | Quasi-experiment (70 students) | Android e-modules improved literacy on bonding | High |
| Nada & Sari | 2020 | Descriptive (25 students) | ChemDraw use showed moderate digital literacy | Medium |
| Nisaa et al. | 2024 | Survey (STEAM PjBL) | STEAM titration projects improved literacy | High |
| Widiyawati | 2021 | STEM digital learning | STEM integration enhanced digital literacy | Medium |
| Ramli | 2020 | Virtual laboratory | Virtual labs strengthened digital literacy | High |
| Fakhrah | 2024 | Blended learning | Blended model improved literacy in chemistry | High |
| Purwianingsih | 2021 | Survey (pre-service teachers) | Moderate literacy among pre-service chemistry teachers | Medium |
| Sanova | 2022 | ICT integration | ICT tools supported digital literacy growth | Medium |
| Yuyun et al. | 2022 | Survey (AR needs) | AR media crucial for abstract chemistry | High |
| Bahriah et al. | 2023 | PBL (chemistry) | PBL supported digital literacy reinforcement | High |

The analysis of digital literacy profiles depicted in Table 2 reveals that the majority of students and pre-service teachers begin with moderate levels of digital literacy. Research by Latip & Faisal (2021) indicates that students engaged in distance learning for chemistry demonstrated merely average digital literacy skills. Similarly, Yulianti et al. (2022) highlighted that over 90% of students exhibited low spatial abilities alongside only moderate digital literacy. Such findings align with (Heidari et al., 2021), who argued that students' digital competencies can significantly influence their academic engagement, particularly in technology-enhanced learning environments. The pressing need for improved digital skills is underscored by Cham et al. (2021), who noted that strategic interventions are essential for enhancing digital competencies among health professional students.

Interventions aimed at improving digital literacy have shown promising results. Nisaa et al. (2024) demonstrated that STEAM project-based learning effectively enhanced students' digital literacy, fostering an engaging educational climate. Dewi et al. (2022) also support this assertion, revealing that the use of Android-based e-modules led to significant improvements in digital literacy among students. Such findings resonate with (Perdana et al., 2019), who found that online simulation learning significantly enhances students' digital skills. Furthermore, Männistö et al. (2019) highlighted the potential of digital interventions to promote collaborative learning, reinforcing the importance of incorporating innovative strategies in educational contexts to boost digital literacy levels.

The effectiveness of structured digital learning strategies is critical as they not only augment students' digital literacy but also prepare them to navigate increasingly complex digital environments. The potential for integrating various digital tools into the curriculum is vast, as evidenced by studies affirming that targeted digital competence training enhances both learning and engagement. Additionally, the advantages of digital literacy programs tailored for specific disciplines have been highlighted in the literature, reinforcing the notion that comprehensive digital education can lead to improved student outcomes. As digital literacy becomes increasingly pivotal in higher education, educators must prioritize effective pedagogical approaches that foster both digital skills and student engagement in their learning processes.

Table 3. Profiles and Levels of Digital Literacy

| Author(s) | Subject(s) | Digital Literacy Level |
|---|---|---|
| Latip & Sutantri (2021) | High school chemistry (distance learning) | Moderate |
| Yulianti et al. (2022) | 922 high school students | Low–Moderate |
| Nada & Sari (2020) | Chemistry undergraduates (ChemDraw) | Moderate |
| Purwianingsih (2021) | Pre-service chemistry teachers | Moderate |
| Nisaa et al. (2024) | High school (STEAM PjBL) | High |
| Dewi et al. (2022) | Chemistry undergraduates (Android e-module) | High (improved significantly) |

The strategies and digital media outlined in the selected studies underscore a significant shift towards interactive, technology-enhanced pedagogy in chemistry education. Among the most frequently reported approaches are Android-based e-modules and Augmented/Virtual Reality (AR/VR) technologies, utilized in multiple studies. These tools exemplify modern educational techniques that foster active learning and student engagement. For instance, project-based learning (PBL) integrated with STEM approaches has been shown to enhance students' conceptual understanding and application skills in real-world contexts (Anggareni Kussudarto & Rosdiana, 2024; binti Zakeri et al., 2023). Furthermore, utilizing game-based learning and virtual laboratories presents opportunities for students to experiment and collaborate, crucial elements identified by researchers as enhancing educational outcomes (Al Hamad et al., 2024). The increasing emphasis on these interactive strategies reflects a broader trend in educational reform aimed at igniting student curiosity and facilitating deeper learning experiences across disciplines (Munna et al., 2023).

Additionally, the effectiveness of integrated digital tools in chemistry education has been recognized in various studies. The integration of innovative software like ChemDraw, alongside hands-on methodologies such as STEAM project-based learning, cultivates a holistic understanding of chemistry while nurturing critical thinking skills (Samsudin et al., 2020). This approach aligns with findings that emphasize the benefits of collaborative learning environments—enhancing not just subject-specific knowledge but also essential competencies for the 21st century (Prajoko et al., 2023). Moreover, the utilization of digital platforms allows for diverse instructional methods that cater to various learning styles, thereby fostering inclusivity and broadening student engagement (Chan & Nagatomo, 2021). As educators continue to implement these cutting-edge techniques, it is essential to monitor their impact on student outcomes, ensuring that instructional practices evolve in line with both technological advancements and pedagogical best practices.

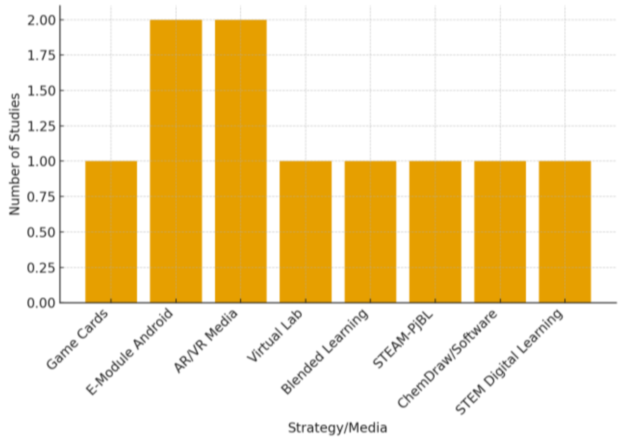
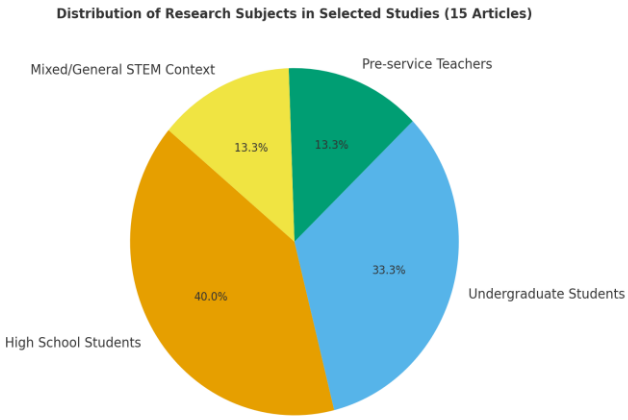



Figure 2. Strategies and Digital Media in Chemistry Literacy Studies

In discussion, the findings suggest that strengthening digital literacy in chemistry education requires more than mere access to digital tools. Effective implementation depends on pedagogical alignment, teacher preparedness, and students' active engagement with digital platforms. The results align with global calls to integrate 21st-century skills, particularly critical thinking, collaboration, and problem-solving, into science education. Furthermore, the consistent emphasis on open access digital resources highlights an important equity dimension, ensuring that students from diverse backgrounds can equally benefit from innovations in digital chemistry learning.

Figure 3. Distribution of Research Subject in Selected Studies




The distribution of research subjects across the 15 selected studies reveals an important trend in the focus of digital literacy research within chemistry education. The largest proportion, accounting for 40% of the studies, involved high school students as participants. This finding is significant because high school represents a crucial stage in which students encounter increasingly abstract and complex chemistry concepts, such as chemical bonding, stoichiometry, thermodynamics, and reaction kinetics. At this stage, digital literacy plays a transformative role in helping students bridge the gap between macroscopic chemical phenomena and their submicroscopic representations. Tools such as AR/VR simulations, virtual laboratories, and gamified e-modules were particularly effective in high school contexts, as they enabled students to visualize otherwise intangible molecular processes and to engage interactively with chemistry content. The emphasis on high school students also reflects an educational priority: preparing adolescents to navigate the digital demands of higher education and the workforce. By embedding digital literacy in secondary education, these studies sought to ensure that students developed not only subject-specific knowledge but also transferable skills, including critical evaluation of online resources, collaboration in digital spaces, and responsible engagement with technology. This widespread focus suggests that policymakers and curriculum designers recognize the importance of integrating digital literacy into secondary science education as a foundation for broader 21st-century competencies.

A substantial proportion of the reviewed studies (33%) targeted undergraduate students, particularly those majoring in chemistry or science education. These studies emphasized the role of digital literacy in enabling students to conduct more advanced tasks, such as using specialized software like ChemDraw, analyzing complex data sets, or engaging in independent digital research. Unlike high school students, undergraduates are expected to demonstrate higher levels of autonomy and self-directed learning. Consequently, the interventions in these studies often centered on fostering deeper cognitive engagement and problem-solving skills, rather than simply improving technical familiarity with digital tools. For instance, Android-based e-modules in bonding concepts not only improved digital literacy but also reinforced critical understanding of theoretical principles, while crystallography visualization software expanded students' capacity to comprehend three-dimensional structures. Furthermore, undergraduate research subjects often included future science educators, which positioned digital literacy not only as a learning outcome but also as a professional competency essential for effective teaching. The significance of this group lies in their dual role: as learners who benefit directly from enhanced digital skills and as future facilitators who will disseminate those skills to future cohorts of students. The emphasis on undergraduates therefore underscores the continuity of digital literacy development across educational levels, ensuring that the integration of digital competencies in chemistry learning is sustained from early education through to higher academic and professional stages.

Another notable portion of the research focused on pre-service teachers (13%) and studies in broader STEM contexts (13%). The attention to pre-service teachers highlights an urgent need to prepare the next generation of educators to integrate digital tools meaningfully into their pedagogical practices. Findings from these studies indicate that while pre-service teachers often possess moderate levels of digital literacy, they require structured interventions to elevate their skills to professional standards. For instance, studies involving blended learning or project-based approaches demonstrated that when pre-service teachers actively engaged with digital tools in authentic teaching simulations, their digital literacy improved alongside their pedagogical competence. This has direct implications for teacher education programs, which must prioritize digital pedagogy training as part of their core curricula. Similarly, the smaller but meaningful share of studies focusing on mixed or general STEM contexts indicates an awareness of interdisciplinary approaches to digital literacy. Chemistry, as a discipline, often intersects with physics, biology, and engineering, and the integration of digital literacy across STEM ensures that students are equipped with versatile competencies applicable in multidisciplinary environments. The inclusion of this category also reflects a recognition that digital literacy is not subject-bound but a universal skill that empowers learners to navigate complex information landscapes across scientific domains. Taken together, these findings illustrate a multi-layered approach to digital literacy development: beginning with foundational skills in high school, deepened through specialized tasks at the undergraduate level, and professionalized through teacher education programs. This layered trajectory reinforces the importance of positioning digital literacy not as an isolated competency but as a lifelong learning continuum within chemistry education.

The findings of this review offer several critical implications for chemistry education and classroom practice. Evidence from the selected studies demonstrates that structured digital interventions—including Android-based e-modules, AR media, virtual laboratories, and STEAM project-based learning—substantially enhance students' digital literacy and conceptual understanding of chemistry. This suggests that digital literacy should not be treated as an optional supplement but rather as a central pedagogical component. Teachers are encouraged to design lessons that actively integrate digital tools to foster collaboration, creativity, and critical thinking, moving beyond traditional lecture-based methods. However, the effectiveness of these approaches depends heavily on teacher preparedness. Continuous professional development is therefore essential to equip educators not only with the technical knowledge to use digital platforms but also with the pedagogical skills to employ them in ways that truly support student learning.

From a broader perspective, these findings also point to important policy and research implications. Policymakers should prioritize equitable access to digital resources by investing in infrastructure, supporting open access platforms, and reducing barriers for schools in underserved areas. Such initiatives are crucial to ensuring that students from diverse backgrounds can equally benefit from digital innovations in chemistry education. At the same time, further research is needed to move beyond short-term experimental studies and explore the long-term impact of digital literacy interventions on students' academic outcomes, digital citizenship, and readiness for future careers. This review highlights that digital literacy must be institutionalized as a core competency in chemistry education, ensuring that both teachers and students are adequately prepared to thrive in the increasingly digital and interconnected world of the 21st century.

## Conclusion

This literature review concludes that strengthening digital literacy in chemistry education requires the integration of innovative instructional strategies and digital media that go beyond simple access to technology. Across the 15 reviewed studies, evidence consistently showed that approaches such as Android-based e-modules, AR applications, STEAM project-based learning, game-based learning, and virtual laboratories significantly improved students' digital literacy while also enhancing their conceptual understanding of chemistry. Most learners initially demonstrated moderate levels of digital literacy, yet structured interventions effectively elevated these competencies to higher levels. The findings emphasize that successful digital literacy development depends not only on the availability of digital tools but also on pedagogical alignment, teacher preparedness, and active student engagement. Consequently, digital literacy should be considered a core competency in chemistry education, aligning with the broader agenda of 21st-century skills to ensure equitable, meaningful, and future-oriented learning experiences.

## References

Abd Majid, N. A., & Majid, N. Abd. (2018). Augmented Reality to Promote Guided Discovery Learning for STEM Learning. *International Journal on Advanced Science Engineering and Information Technology*. https://doi.org/10.18517/ijaseit.8.4-2.6801

Abdinejad, M., Ferrag, C., Qorbani, H. S., & Dalili, S. (2021). Developing a Simple and

Cost-Effective Markerless Augmented Reality Tool for Chemistry Education. *Journal of Chemical Education*. https://doi.org/10.1021/acs.jchemed.1c00173

Abdul Rahim, A. S., & Chuah, K.-M. (2024). Design and Implementation of Interactive, Remote Online Escape Rooms in Medicinal Chemistry. *The Electronic Journal of E-Learning*. https://doi.org/10.34190/ejel.22.4.3185

Aini, D. N. (2023). *Improving Civic Intelligence Through Citizenship Education Based on Digital Literature Curriculum*. https://doi.org/10.2991/978-2-38476-096-1_15

Al Hamad, N. M., Adewusi, O. E., Unachukwu, C. C., Osawaru, B., & Chisom, O. N. (2024). A Review on the Innovative Approaches to STEM Education. *International Journal of Science and Research Archive*. https://doi.org/10.30574/ijsra.2024.11.1.0026

Anggareni Kussudarto, R. E., & Rosdiana, L. (2024). Comparative Study of PJBL-STEM Learning Models: Analyzing Similarities and Differences Between Two Research Articles. *Science Education and Application Journal*. https://doi.org/10.30736/seaj.v6i2.1092

Arief, U. M., Wibawanto, H., & Nastiti, A. L. (2018). *Augmented Reality Technology for Vocational Education the Disruption Era*. https://doi.org/10.2991/aptekindo-18.2018.16

Arissaputra, R., Sobandi, A., Sentika, S., Sultan, Mokh. A., & Nurwita Wijaya, N. P. (2023). Trend Analysis Using Bibliometric Study on Digital Literacy in Education. *International Journal of Humanities Education and Social Sciences (Ijhess)*. https://doi.org/10.55227/ijhess.v3i3.667

Badilla Quintana, M. G., Valenzuela, E. S., & Arias, M. S. (2020). Augmented Reality as a Sustainable Technology to Improve Academic Achievement in Students with and Without Special Educational Needs. *Sustainability*. https://doi.org/10.3390/su12198116

Berber, Ş., Deveciyan, M. T., & Alay, H. K. (2023). Digital Literacy Level and Career Satisfaction of Academics. *İnsan Ve Toplum Bilimleri Araştırmaları Dergisi*. https://doi.org/10.15869/itobiad.1343893

binti Zakeri, N. N., Hidayat, R., binti Sabri, N. A., binti Yaakub, N. F., Balachandran, K. S., & binti Azizan, N. I. (2023). Creative Methods in STEM for Secondary School Students: Systematic Literature Review. *Contemporary Mathematics and Science Education*. https://doi.org/10.30935/conmaths/12601

Braslauskienė, R., Turauskienė, E., & Jacynė, R. (2024). The Potential of Digital Tools for Developing Pre-School Children's Language Skills: Teachers' Experiences. *Regional Formation and Development Studies*. https://doi.org/10.15181/rfds.v42i1.2607

Butar, S. B., Mulyadi, H., & Ramdhany, M. A. (2024). The Mediating Role of Work Motivation in the Impact of Training on Teachers' Digital Literacy. *Lectura Jurnal Pendidikan*. https://doi.org/10.31849/lectura.v15i2.20646

Çetinkaya, S. (2024). Field Experience and Digital Technology-Based Literacy Instruction. *International Journal of Educational Research Review*. https://doi.org/10.24331/ijere.1404019

Cham, K. M., Edwards, M.-L., Kruesi, L., Celeste, T., & Hennessey, T. (2021). Digital Preferences and Perceptions of Students in Health Professional Courses at a Leading Australian University: A Baseline for Improving Digital Skills and Competencies in Health Graduates. *Australasian Journal of Educational Technology*. https://doi.org/10.14742/ajet.6622

Chan, M.-N., & Nagatomo, D. (2021). Study of STEM for Sustainability in Design Education: Framework for Student Learning and Outcomes with Design for a Disaster Project. *Sustainability*. https://doi.org/10.3390/su14010312

Clapson, M. L., Gilbert, B., & Musgrove, A. (2020). Race to the Reactor and Other Chemistry Games: Game-Based and Experiential Learning Experiences in Materials and Polymer Chemistry. *Journal of Chemical Education*. https://doi.org/10.1021/acs.jchemed.0c01135

Dewi, C. A. (2021). *The Effect of Contextual Collaborative Learning Based Ethnoscience to Increase Student' s Scientific Literacy Ability*. *18*(3), 525–541.

Elías, M., Pérez, J., Rosario Cassot, M. del, Carrasco, E. A., Tomljenovic, M., & Zúñiga, E. A. (2022). Development of Digital and Science, Technology, Engineering, and Mathematics Skills in Chemistry Teacher Training. *Frontiers in Education*. https://doi.org/10.3389/feduc.2022.932609

Hamsiah, A., Angreani, A. V., Hazairin Zubair, A. G., Rahmadhanningsih, S., Swandi, A., Rahim, A., & Rizal, A. (2024). Transforming Education in Coastal Indonesia: A Survey of Digital Literacy and Competence Among Educators. *International Journal of Religion*. https://doi.org/10.61707/59p9jn39

Hebebci, M. T., Bertiz, Y., & Alan, S. (2020). Investigation of Views of Students and Teachers on Distance Education Practices During the Coronavirus (COVID-19) Pandemic. *International Journal of Technology in Education and Science*. https://doi.org/10.46328/ijtes.v4i4.113

Heidari, E., Mehrvarz, M., Marzooghi, R., & Stoyanov, S. (2021). The Role of Digital Informal Learning in the Relationship Between Students' Digital Competence and Academic Engagement During the <scp>COVID</Scp>-19 Pandemic. *Journal of Computer Assisted Learning*. https://doi.org/10.1111/jcal.12553

Holm, P. (2024). Impact of Digital Literacy on Academic Achievement: Evidence from an Online Anatomy and Physiology Course. *E-Learning and Digital Media*. https://doi.org/10.1177/20427530241232489

Kardeş, S. (2020). Erken Çocukluk Döneminde Dijital Okuryazarlık. *İnönü Üniversitesi Eğitim Fakültesi Dergisi*. https://doi.org/10.17679/inuefd.665327

Kiryakova, G., & Kozhuharova, D. (2024). The Digital Competences Necessary for the Successful Pedagogical Practice of Teachers in the Digital Age. *Education Sciences*. https://doi.org/10.3390/educsci14050507

Kornienko, D. V, & Mishina, S. V. (2023). Implementation of Digital Education Tools in the Pedagogical Community. *Journal of Higher Education Theory and Practice*. https://doi.org/10.33423/jhetp.v23i13.6370

Kurniasih, N. (2023). Digital Literacy: Education for Safe Internet Usage. *Engagement Jurnal Pengabdian Kepada Masyarakat*. https://doi.org/10.29062/engagement.v7i1.1534

Lathwesen, C., & Eilks, I. (2024). Can You Make It Back to Earth? A Digital Educational Escape Room for Secondary Chemistry Education to Explore Selected Principles of Green Chemistry. *Journal of Chemical Education*. https://doi.org/10.1021/acs.jchemed.4c00149

Latip, A., & Faisal, A. (2021). Upaya Peningkatan Literasi Sains Siswa Melalui Media Pembelajaran IPA Berbasis Komputer. *Jurnal Pendidikan Uniga*. https://doi.org/10.52434/jp.v15i1.1179

Listiawati, M., Hartati, S., Agustina, R. D., Putra, R. P., & Andhika, S. (2022). Analysis of the Use of LabXChange as a Virtual Laboratory Media to Improve Digital and Information Literacy for Biology Education Undergraduate Students. *Scientiae Educatia*. https://doi.org/10.24235/sc.educatia.v11i1.10278

Marín, V. I., & Castañeda, L. (2022). *Developing Digital Literacy for Teaching and Learning*. https://doi.org/10.1007/978-981-19-0351-9_64-1

Maya, L., & Suseno, M. (2022). Investigating the Incorporation of Digital Literacy and 21st-Century Skills into Postgraduate Students' Learning Activities. *Ele Reviews English Language Education Reviews*. https://doi.org/10.22515/elereviews.v2i1.5121

Mazzuco, A., Krassmann, A. L., Reategui, E., & Gomes, R. S. (2022). A systematic review of augmented reality in chemistry education. *Review of Education*, *10*(1). https://doi.org/10.1002/rev3.3325

Mulyani, S., Lutfiyani, A., & Mahardiani, L. (2023). Development of a Virtual Chemistry Laboratory Based on Green Chemistry to Increase Technological Literacy Focusing on Factors Affecting Reaction Rates. *Paedagogia*. https://doi.org/10.20961/paedagogia.v26i1.71851

Munna, A. S., Ilham, D., & Sandi, K. (2023). Bridging the Gap. *Jtest*. https://doi.org/10.51629/jtest.v1i1.169

Nikou, S., & Aavakare, M. (2021). An Assessment of the Interplay Between Literacy and Digital Technology in Higher

Education. *Education and Information Technologies*. https://doi.org/10.1007/s10639-021-10451-0

Oliynyk, V. V, Gushchyna, N. I., Kondratova, L., & Касьян, С. П. (2024). Developing Digital Competence of Teachers in Postgraduate Education Using Google Workspace for Education. *Cte Workshop Proceedings*. https://doi.org/10.55056/cte.662

Pangrazio, L., Godhe, A.-L., & González Ledesma, A. E. (2020). What Is Digital Literacy? A Comparative Review of Publications Across Three Language Contexts. *E-Learning and Digital Media*. https://doi.org/10.1177/2042753020946291

Prajoko, S., Sukmawati, I., Maris, A. F., & Wulanjani, A. N. (2023). Project Based Learning (PjBL) Model with STEM Approach on Students' Conceptual Understanding and Creativity. *Jurnal Pendidikan Ipa Indonesia*. https://doi.org/10.15294/jpii.v12i3.42973

Quraishi, T., Ulusi, H., MUHID, A., Hakimi, M., & OLUSI, M. R. (2024). Empowering Students Through Digital Literacy: A Case Study of Successful Integration in a Higher Education Curriculum. *Journal of Digital Learning and Distance Education*. https://doi.org/10.56778/jdlde.v2i8.208

Repanovici, A., Borcoman, M., Bejinaru Mihoc, A. M., & Babii, E.-A. (2024). Understanding Information Literacy Engagement Patterns of Generation Z. *Investigación Bibliotecológica Archivonomía Bibliotecología E Información*. https://doi.org/10.22201/iibi.24488321xe.2024.98.58850

Rizvan, A., Luiza, A., & Anna, Y. (2023). Enhancing Chemistry Education's Relevance and Comprehension Through Immersive Virtual Reality. *E3s Web of Conferences*. https://doi.org/10.1051/e3sconf/202345106013

Salisbury, F., Hannon, J., & Peasley, J. (2024). Framing the Digitally Capable University. *Ascilite Publications*. https://doi.org/10.14742/apubs.2017.760

Samsudin, M. A., Jamali, S. M., Md Zain, A. N., & Ebrahim, N. A. (2020). The Effect of STEM Project Based Learning on Self-Efficacy Among High-School Physics Students. *Journal of Turkish Science Education*. https://doi.org/10.36681/tused.2020.15

Shan Wong, C. H., Tsang, K. C. K., & Chiu, W.-K. (2021). Using Augmented Reality as a Powerful and Innovative Technology to Increase Enthusiasm and Enhance Student Learning in Higher Education Chemistry Courses. *Journal of Chemical Education*. https://doi.org/10.1021/acs.jchemed.0c01029

Sinaga, R., Simanjuntak, S. E., Ginting, M. N., Tarigan, F., & Pinem, A. B. (2024). Empowering Digital Literacy Through Wattpad: Bridging Creativity, Reading, and Writing in Education. *Jurnal Pengabdian Masyarakat Dan Riset Pendidikan*. https://doi.org/10.31004/jerkin.v2i3.237

Srivastava, S., & Dangwal, K. L. (2021). Digital Competence: Where Do the Higher Education Teachers Stand? *Universal Journal of Educational Research*. https://doi.org/10.13189/ujer.2021.091005

Thu Hoài, V. T., Son, P. N., Thuận An, Đ. T., & Nguyen, V. A. (2024). An Investigation into Whether Applying Augmented Reality (AR) in Teaching Chemistry Enhances Chemical Cognitive Ability. *International Journal of Learning Teaching and Educational Research*. https://doi.org/10.26803/ijlter.23.4.11

Yawan, H. (2022). Augmented Reality Application: Current Status, Opportunities, and Challenges of Indonesian Secondary Education Context. *Edutec Journal of Education and Technology*. https://doi.org/10.29062/edu.v5i3.327

Yontar, A. (2019). Öğretmen Adaylarının Dijital Okuryazarlık Düzeyleri. *Ana Dili Eğitimi Dergisi*. https://doi.org/10.16916/aded.593579