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Digital Literacy Integration in Biology Education: A Systematic Literature Review on Effectiveness and Implementation Challenges

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Abstract
This study examines the integration of digital literacy in biology learning through a systematic analysis of research articles published between 2019 and 2024. The aim of this review is to identify its effectiveness, explore the associated challenges, and formulate implementation patterns of digital literacy in enhancing the quality of biology education. The findings indicate that digital literacy contributes positively to improving students' cognitive learning outcomes and higher-order thinking skills. The ability to access, manage, and evaluate digital information has been shown to support a deeper understanding of complex biological concepts. In addition, the integration of digital literacy through innovative learning models such as STEM, HOTS-oriented instruction, and problem-based learning enhances student engagement and active participation in the learning process. However, the implementation of digital literacy continues to face several challenges, including limited infrastructure, disparities in digital competencies among students, and variations in teachers' ability to integrate technology effectively. These findings highlight that the effectiveness of digital literacy is strongly dependent on the quality of instructional design and the readiness of the educational ecosystem. Therefore, a more integrated and sustainable approach is required to optimize the role of digital literacy in biology learning, ensuring that it remains adaptive and relevant to the demands of 21st-century education.

Keywords: Biology learning; Digital literacy; Higher-order thinking skills (HOTS); Systematic review; Technology integration.

INTRODUCTION

The transformation of education in the digital era necessitates a paradigmatic shift from knowledge transmission–oriented instruction toward the cultivation of 21st-century competencies that are adaptive to rapid technological advancements. Within this evolving landscape, digital literacy has emerged as a pivotal competency that learners must possess to navigate the increasing complexity of information in a globalized world (Patigu et al., 2024). Digital literacy extends beyond mere technical proficiency in operating digital devices; it also encompasses higher-order cognitive abilities, including the capacity to access, critically evaluate, and effectively manage information (Ifadah & Prastiwi, 2021). This need is particularly salient in biology education, which is characterized by complex subject matter requiring deep conceptual understanding (Ananda et al., 2023).

Previous studies indicate that students' levels of digital literacy in biology learning remain within the moderate range, thereby necessitating targeted instructional strategies to enhance these competencies (Asmadi, 2023). Further research suggests that digital literacy comprises multiple interconnected dimensions, including information access, evaluation, utilization, and digital safety, all of which must be systematically developed within the learning process (Yeyendra et al., 2024). The implementation of technology-based learning approaches, such as online learning environments, has been shown to contribute to improvements in students' digital literacy, although its effectiveness is contingent upon the readiness of technological infrastructure and teacher competence (Ifadah & Prastiwi, 2021). Moreover, empirical findings reveal that the integration of digital literacy into biology instruction can significantly enhance

students' ability to process and comprehend scientific information more deeply (Muyasaroh et al., 2021).

Literature in biology education further underscores that the development of literacy both scientific and digital is a fundamental component in fostering learning that aligns with the demands of the 21st century (Enjelly, Fadilah, 2024). The interplay between digital literacy and scientific literacy suggests that the ability to interpret and engage with digital information strengthens students' conceptual understanding of scientific phenomena (Makhdum, 2022). Additionally, the integration of technology into instructional practices facilitates more contextualized and interactive learning experiences (Yani et al., 2026). The rapid advancement of educational technologies has also led to the emergence of diverse digital-based learning models that hold significant potential for improving the quality of biology education (Cenita & De Guzman, 2023).

Collectively, these studies demonstrate that digital literacy plays a strategic role in enhancing the quality of biology learning across cognitive, affective, and 21st-century skill domains (Patigu et al., 2024). Its implementation contributes to the development of critical thinking and problem-solving abilities among learners (Yeyendra et al., 2024). Nevertheless, the integration of digital literacy in biology education continues to face substantial challenges, including limited technological infrastructure, insufficient teacher preparedness, and disparities in digital access among students (Ifadah & Prastiwi, 2021). These constraints constitute critical factors influencing the overall effectiveness of digital literacy integration in instructional processes (Muyasaroh et al., 2021).

Despite the growing body of research on digital literacy in biology education, the majority of studies tend to focus either on descriptive analyses of students' digital literacy levels or on the effectiveness of specific instructional models in isolation. Comprehensive investigations that simultaneously address both the effectiveness and the implementation challenges of digital literacy integration remain relatively scarce, particularly in the form of systematic literature reviews that consolidate recent empirical findings.

This study offers a novel contribution by providing an integrative synthesis of the literature that not only examines the effectiveness of digital literacy integration in biology education but also critically identifies the associated implementation challenges. Such an approach is expected to yield a more holistic and in-depth understanding of the issue, thereby contributing conceptually to the development of more adaptive and contextually grounded digital literacy–based instructional strategies in biology education. Accordingly, the objective of this study is to systematically analyze the effectiveness of digital literacy integration in biology learning and to identify its implementation challenges based on recent literature, with the aim of informing the development of more innovative and relevant educational practices aligned with the demands of the 21st century

METHODS

This This study employs a systematic literature review design to identify and synthesize findings related to the integration of digital literacy in biology learning. This approach was chosen because it is capable of producing a comprehensive, systematic, and transparent synthesis of previous studies (Snyder, 2019). The research procedure refers to the PRISMA guidelines to ensure clarity in the selection stages and to enhance the replicability of the study (Page et al., 2021).

The literature criteria were determined through clearly defined inclusion and exclusion boundaries. These criteria can be seen as follows:

Table 1. Inclusion and Exclusion Criteria

Aspect	Inclusion Criteria	Exclusion Criteria
Publication Type	Reputable journal articles and conference proceedings (*peer-reviewed*)	Non-academic articles, opinions, editorials
Topic	Digital literacy in biology learning or science education	Not relevant to digital literacy or biology learning
Year Range	Publications from 2019–2024	Publications خارج that time range
Language	English or Bahasa Indonesia	Languages other than English and Bahasa Indonesia
Access	Full-text available	Full text not available

These criteria were established to ensure that the analyzed literature reflects the most recent research developments and possesses adequate academic quality (Paul & Criado, 2020; Booth et al., 2021).

The databases used in the literature search included Scopus, Web of Science, ScienceDirect, and ERIC as primary sources, with Google Scholar serving as a supplementary source to broaden the scope of the search (Gusenbauer & Haddaway, 2020). The search strategy was conducted using combinations of keywords based on Boolean operators such as "digital literacy" AND "biology learning," "science education" AND "digital competence," as well as "technology integration" AND "learning effectiveness" AND "implementation challenges" to ensure both the relevance and comprehensiveness of the search results (Brereton et al., 2007).

The literature selection process was conducted in a staged manner following the PRISMA flow. This process was carried out systematically to minimize selection bias and enhance the validity of the findings. A more detailed overview of the literature selection process is presented in the figure below:

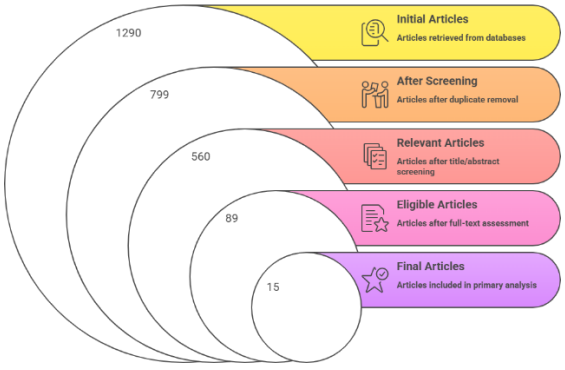

Figure 1. Article Selection Process

Data analysis was conducted using a thematic analysis approach to identify patterns, categories, and key themes emerging from the reviewed literature. The analytical stages included data coding, grouping codes into overarching themes, and conducting a comprehensive interpretation of the findings (Braun & Clarke, 2021). Data synthesis was performed narratively to integrate findings from studies with diverse approaches and research designs, thereby generating a holistic understanding of the effectiveness and challenges of integrating digital literacy in biology education (Popay et al., 2006)

RESULT AND DISCUSSION

Table 2 presents a comprehensive synthesis of the 15 selected articles analyzed in this study, representing a range of research approaches, study designs, and implementation contexts of digital literacy in biology learning during the period 2019–2024. The information presented

includes author details, research titles, year of publication, and the main findings of each study. The purpose of compiling this table is not only to summarize prior research findings, but also to identify patterns, similarities, and differences related to the effectiveness and dynamics of digital literacy implementation in biology education in a more systematic manner.

Table 2. Eligible Articles

No	Authors	Title	Year	Result
1	C Utama, Sajidan, J Nurkamto, Wiranto	Investigating Biology pre-service teacher perception of general Biology and digital literacy	2019	The results show that respondents feel essential and need to master the latest technology to be integrated into biology learning. 95% of respondents thought that biology learning with technology is more exciting and fun. This condition indicates that respondents are ready to be taught biology using the latest technology.
2	Puput Tri Utami, Nur Ducha (Utami & Ducha, 2020)	The Validity and Legibility of Digital Literacy-Based Reproductive System Flipbook to Improve The Critical Thinking Skills of Grade 11Th High School Students	2020	The results of the validation showed very valid categories in each component with the average percentage of the presentation was 87.5%, content eligibility 96.3%, linguistic 91.7% , and critical thinking 98.3%. The validation components got 93.5% average percentage with a very valid category. The level of legibility of the flipbook showed level 11 with the appropriate category for high school students. Based on the results of the study, the developed flipbook was declared to be very valid and had an appropriate level of legibility for high school students.
3	Yundri Akbar, Anggi Fitri, Zalisman, Muhammad Ilham Syarif, Niswah, Parlindungan Simbolon, Ayu Purnamasari S, Nofita Tryana, Zaitun Abidin (Akhyar et al., 2021)	Contribution of Digital Literacy to Students' Science Learning Outcomes in Online Learning	2021	The results showed that the calculation of the correlation coefficient of 4.412 is greater than 2.034 with a significance value of 0.000 less than an alpha value of 0.05, a coefficient of determination of 0.371 x 100% of 37.1%. Based on these results, it can be concluded that there is a positive and significant effect on the application of digital literacy on students' science learning outcomes.
4	Nur Hafiza, Hanum Mukti Rahayu, Adi Pasah Kahar (Hafiza et al., 2022)	The Relationship Between Digital Literacy and Learning Outcomes inBiology Learning forStudents	2022	The results of the student biology study of students get an average of 68.02 gifts in the intermediate class. Product correlation analysis between x variables and y variables show that r recount (0.290) > t-table (1.987) so that there is a link between digital literacy and the

No	Authors	Title	Year	Result
				study of the biological student vii class 12 countries
5	Sarini Rahayu, Wiwi Isnaeni, Masturi Masturi (Rahayu et al., 2022)	Critical Thinking Skills and Digital Literacy of High School Students in Science Learning Using E-Learning with STEM Vision	2022	The results showed that in general there was a significant difference in digital literacy between the experimental class and the control class, In addition, there is a significant difference in critical thinking skills between the experimental class and the control class and there is a significant difference in critical thinking skills and digital literacy between the experimental class and the control class. Learning STEM Vision E-Learning can be implemented well, students and teachers give a positive response to learning STEM Vision E-Learning on the material circulation system. Suggestions in this study need a STEM approach between teachers and students so that online learning takes place without obstacles.
6	Andi Muhamad Yusuf, Saiful Hidayatullah, Dian Tauhidah (Yusuf et al., 2022)	The relationship between digital and scientific literacy with biology cognitive learning outcomes of high school students	2022	The results showed that there was a positive and significant relationship between digital literacy and scientific literacy with cognitive biology learning outcomes, with a significance value of 0.00 < 0.05, a large correlation value of 0.474 (medium correlation), and a coefficient of determination of 20.4%. It is important for teachers and students to apply digital literacy and scientific literacy to improve cognitive learning outcomes.
7	Wisye Hehakaya, Muhammad Nur Matdoan, Dominggus Rumahlatu (Hehakaya et al., 2022)	Integrating STEAM with PjBL and PBL on biology education: Improving students' cognitive learning results, creative thinking, and digital literacy	2022	The research results indicate that the integration of STEAM with PjBL and PBL learning models significantly affects students' cognitive learning results and creative thinking ($p<0.05$). However, the integration of STEAM and PjBL and PBL learning models does not significantly affect students' digital literacy ($p>0.05$). The integration of STEAM with PjBL and PBL learning models provides innovation in implementing the two learning models, which improves the learning steps and the learning

No	Authors	Title	Year	Result
				process.
8	Fathia Zaitun Azzahro, Bunga Ihda Norra, Chusnul Adib Ahmad (Azzahro et al., 2023)	The Relationship of Digital Literacy Ability with Students' Cognitive Learning Outcomes	2023	The results showed that there was no significant relationship between digital literacy skills and the cognitive learning outcomes of Temanggung MAN students in excretion system material with a significant value of 0.307 > 0.05.
9	Fariza Batyrkanovina (Nietbaeva, 2023)	Digital Literacy In Biology Education Through Mobile Learning Technologies	2023	The results demonstrate a marked improvement in students' digital literacy, with a notable increase in their ability to navigate, evaluate, and create information using digital technologies. Furthermore, the integration of mobile technologies was found to enhance student engagement and understanding of biology concepts.
10	Kristin Sangur, Dominggus Rumahlatu (Sangur & Rumahlatu, 2023)	PjBL-HOTS: Integration of learning in improving critical thinking and digital literacy of biology education students	2023	The results showed that the learning model significantly affected students' critical thinking skills with $0.017<\alpha=0.05$. Meanwhile, the learning model did not significantly affect students' digital literacy, which was indicated with $0.249>\alpha=0.05$. This result shows that the PjBL-HOTS learning model with its complex syntax can empower students' critical thinking skills. Moreover, both the PjBL-HOTS and PjBL learning models can train students' ability to search information from digital
11	Nuranisha Binazrul Kinayoh, Reni Ambarwati (Kinayoh & Ambarwati, 2023)	The Development of Flipbook Based on Digital Literacy on Animalia-Vertebrates of High School Student Grade 10th	2023	The results showed that digital literacy-based flipbooks were declared valid in a scale of 3.8 and an overall average percentage score of 96.5%. The practicality of flipbooks was seen from the results of the readability test on level of 10 that shows flipbooks are suitable for X grade of high school students; the implementation test with 100% percentage score; the positive response of practicality by Biology teachers obtained percentage of 90.2%; and the student response obtained percentage of 97,8%. Based on those parameters, it concluded that the digital literacy-based flipbook in which developed for Animalia-Vertebrates materials

No	Authors	Title	Year	Result
				on X grade of high school is valid and practical.
12	Nia Maulidhia Ibrahim, Yayan Sanjaya, Mimin Nurjhani (Ibrahim et al., 2024)	Effectiveness of Biology Learning to Improve Digital Literacy and Higher Order Thinking Skills on the Concept of Digestive System	2024	The results showed that there was a significant difference in the average high-level thinking skills of students between the experimental class and the control class. Showing the T-test number on the value of digital literacy skills shows the number (2-tailed = 0.000) < α (0.05), it means that there is a difference in the effectiveness of using HOTS-based e-learning with ordinary e-learning to improve students' digital literacy skills. The N-Gain score criteria for using HOTS-based e-learning to improve digital literacy skills fall into the medium category (N-gain = 0.56) and the use of HOTS-based e-learning to improve higher order thinking skills in the medium category (N-gain = 0.83).
13	Ridho Ilafi Sukma, Widi Purwianingsih, Amprasto (Sukma et al., 2024)	An analysis of digital literacy skills of high school students in biology	2024	The results indicate that the digital literacy of tenth-grade high school students with an average score of 44% is in the fair category. Meanwhile, the results for each aspect of the digital literacy indicator obtained different scores, namely internet searching at 47% (fair), hypertext navigation at 27% (fair), evaluating information at 40.32% (fair), and synthesizing information at 60.48% (good).
14	Andi Muhammad Miftah Farid, Siti Zubaidah, Munzil (Farid et al., 2024)	Profile analysis of digital literacy skills of biology education students	2024	These results suggest that more attention is needed to digital literacy development in biology education at all levels. These findings emphasized the importance of further and holistic empowerment of digital literacy skills among biology education students, particularly in evaluating and considering the source/effect of messages. Improvements in these areas and studies are critical to preparing students for academic and professional success and fostering their engagement with society in an increasingly digitalized world. Future research efforts should focus on implementing targeted interventions to improve

No	Authors	Title	Year	Result
				digital literacy in programs and comparing the level of digital literacy across different biology education courses in different institutions.
15	Salwa Rezeqi, Erina Saputri Ritonga, Siti Liza Khairani (Rezeqi et al., 2024)	Analysis of students' digital literacy ability in the Spermatophyta course	2024	The results showed that digital literacy skills in Biology Education were in the very good category 81.30. Student abilities are very good in content creation, communication, collaboration, information but for critical thinking skills, evaluation and operational skills are good.

As The results presented in Table 2 indicate that the integration of digital literacy in biology learning yields relatively consistent positive impacts, particularly in enhancing cognitive learning outcomes. The significant positive relationships identified across several studies suggest that students' abilities to access, manage, and evaluate digital information contribute to a deeper understanding of complex biological concepts. In addition, digital literacy is also associated with the development of higher-order thinking skills, especially critical thinking, as evidenced by the implementation of technology-based learning models such as HOTS-oriented e-learning, STEM, and Project-Based Learning (PjBL). These findings emphasize that digital literacy functions not merely as a technical tool, but also as a medium that fosters analytical and reflective thinking processes in learning.

However, not all studies report consistent results, indicating that the effectiveness of digital literacy is context-dependent and influenced by instructional design, the learning models employed, as well as the readiness of both teachers and students. In terms of learning media, the use of digital tools such as flipbooks, mobile learning applications, and e-learning platforms has been shown to enhance student engagement and motivation, although students' digital literacy skills generally remain at a moderate level, with notable weaknesses in information evaluation and critical thinking. Furthermore, the effectiveness of digital literacy tends to be more pronounced when integrated with innovative instructional models. Overall, digital literacy plays a strategic role in biology education, yet it requires well-structured instructional design, improved teacher competence, and optimized technology integration to function effectively in supporting adaptive and critical learning environments.

Discussion

Effectiveness of Digital Literacy Integration in Biology Learning

The integration of digital literacy in biology learning plays a crucial role in improving students' learning outcomes, particularly in the cognitive domain. The use of digital technologies enables access to a wide range of learning resources, such as interactive videos, simulations, and scientific databases, which help students understand complex and abstract biological concepts in a more concrete manner. The visualizations provided through digital media bridge the limitations of conventional instruction while also reducing misconceptions that often arise in microscopic or dynamic biological topics. As a result, the learning process becomes more effective in fostering deep conceptual understanding.

Digital literacy also promotes student-centered learning, where learners actively construct knowledge through independent exploration. Students are able to search for, compare, and evaluate information from various digital sources, making the learning process more active rather than passive. Interaction with diverse resources strengthens the constructivist approach, which emphasizes knowledge construction through meaningful learning experiences.

Consequently, students do not merely receive information but also process and interpret it within relevant learning contexts.

Empirical findings indicate that the integration of digital technologies in science education enhances conceptual understanding, learning retention, and student engagement in the learning process (Schindler et al., 2017; Zhang et al., 2004). Systematically designed digital learning platforms have been shown to create interactive and responsive learning environments that accommodate students' needs. Moreover, technology-based learning provides flexibility in terms of time and space, allowing students to revisit materials and deepen their understanding independently. This contributes to stronger long-term memory retention and improved overall learning outcomes.

In addition to cognitive gains, digital literacy also enhances students' motivation and engagement in learning (Bond et al., 2021). Interactive and contextual learning environments create more engaging learning experiences that are relevant to real-life situations. The downstream impact of these conditions is the development of higher-order thinking skills, such as analysis, evaluation, and problem-solving abilities. Therefore, the integration of digital literacy in biology learning not only strengthens conceptual understanding but also develops more comprehensive student competencies that are adaptive to the advancement of science and technology.

Student Digital Literacy Skills Profile

The profile of students' digital literacy skills indicates that most learners are still at a moderate level, with noticeable variation across different competency indicators. Basic skills such as accessing, operating, and using digital technologies tend to be more developed compared to higher-order abilities such as critical thinking, evaluation, and reflection on information. This condition suggests that students are generally at an operational stage, where technology is used primarily as a tool rather than as a medium for analytical and deeper thinking. This finding aligns with previous research indicating that digital literacy tends to develop more rapidly in technical aspects than in higher cognitive domains (Ng, 2012).

The gap between technical proficiency and higher-order cognitive skills represents one of the main challenges in digital literacy development. Students who are accustomed to using technology in daily life do not necessarily possess the ability to assess the validity, relevance, and credibility of the information they encounter. This indicates that technological proficiency does not automatically translate into critical thinking ability. Without adequate evaluative skills, students are at risk of accepting information uncritically without proper verification, which may compromise the quality of knowledge construction. Other studies also highlight that many students struggle to distinguish between valid and unreliable information in digital environments (Wineburg & McGrew, 2019).

Higher-level digital literacy skills such as analysis, synthesis, and evaluation remain the most challenging aspects to develop within educational contexts. These processes require more complex cognitive engagement, where students are expected not only to understand information but also to integrate multiple sources, compare perspectives, and draw logical, evidence-based conclusions. This is supported by findings that suggest the development of 21st-century digital skills still faces challenges in higher-order thinking dimensions (van Laar et al., 2019). Other studies also emphasize that critical thinking skills in digital environments require structured and continuous instruction (Eshet, 2012).

These limitations in advanced digital literacy skills directly affect the quality of students' conceptual understanding. Learning outcomes tend to remain superficial and less integrated when not supported by deep analytical and evaluative processes. Research indicates that weak information evaluation skills are associated with poor scientific knowledge construction (List & Alexander, 2019). Furthermore, studies show that insufficient integration of digital literacy with critical thinking development can hinder optimal learning achievement (van Deursen & van Dijk, 2014). Therefore, systematic efforts are required in biology education to develop digital literacy

comprehensively, not only in technical aspects but also in cognitive and reflective dimensions.

Variations and Inconsistencies in Research Findings

Although various studies indicate positive effects of digital literacy on learning outcomes, the findings are not always consistent and tend to vary. This suggests that the effectiveness of digital literacy in biology learning is not universal, but highly context-dependent. Differences in research outcomes may be influenced by multiple factors, such as research design, instructional approaches, and the diverse characteristics of learners. These variations highlight that successful integration of digital literacy does not depend solely on the availability of technology, but also on how it is implemented within the learning process.

The use of technology in education does not automatically lead to improved learning outcomes if it is not supported by appropriate pedagogical strategies. Technology functions merely as a tool; therefore, its impact is largely determined by the quality of instructional planning and implementation. Poorly designed integration may result in ineffective learning experiences and may even fail to significantly enhance students' understanding. Consequently, alignment between learning objectives, instructional methods, and technology use is essential to ensure optimal learning experiences (Kirkwood & Price, 2014; Tamim et al., 2011).

In addition to pedagogical factors, students' digital readiness also plays an important role in determining the success of digital literacy integration. Students with strong digital literacy skills tend to be more capable of accessing, evaluating, and utilizing information effectively. Conversely, limited digital skills can become a barrier in the learning process, thereby reducing the potential benefits of technology use. This condition indicates that strengthening basic digital literacy skills should be a key consideration in technology-based learning implementation(Pettersson, 2018).

On the other hand, teachers' competence in utilizing technology is also a critical factor influencing learning effectiveness. Teachers are not only required to master subject content but also to integrate technology in a pedagogically and contextually appropriate manner. This includes selecting suitable digital media, designing interactive learning activities, and managing digital classrooms effectively. Thus, the success of digital literacy in biology learning is the result of the interaction among multiple factors, including instructional strategies, students' readiness, and teachers' competence in optimally managing technology.

Challenges in the Implementation of Digital Literacy

The implementation of digital literacy in biology learning continues to face complex challenges, particularly related to limited technological infrastructure and digital access. This inequality results in unequal opportunities among students in utilizing technology as a learning resource, whether in terms of devices, internet connectivity, or supportive learning environments. Consequently, technology-based learning cannot function optimally and may potentially widen the gap in learning quality among students. This condition indicates that the successful integration of digital literacy heavily depends on equitable access and the availability of supporting facilities (Van Dijk, 2020).

The digital divide also leads to significant differences in learning experiences among students. Those with adequate technological access tend to have greater opportunities to explore diverse and interactive learning resources, while those with limited access face obstacles in fully participating in digital learning processes. In addition, unstable internet connectivity remains a major constraint in digital learning, particularly in regions with underdeveloped infrastructure. Studies show that connectivity and device availability are key determinants of successful technology-based learning (Hohlfeld et al., 2017).

On the other hand, teachers' competence in integrating technology into instruction also represents a significant challenge. Teachers are not only expected to master technology but also to apply it pedagogically in alignment with learning objectives. Limitations in this area may lead to suboptimal use of technology, thereby reducing its impact on learning outcomes. Research

indicates that teachers' readiness, confidence, and pedagogical competence in using technology are critical factors in the successful integration of digital literacy (Ertmer & Ottenbreit-Leftwich, 2010). Therefore, improving teachers' competencies through continuous professional development is a strategic step in supporting the implementation of digital literacy-based biology learning.

CONCLUSION

The integration of digital literacy in biology learning has been shown to have a positive impact, particularly in improving students' cognitive learning outcomes and higher-order thinking skills. Digital literacy serves as a facilitator in helping students understand complex biological concepts through the ability to access, manage, and evaluate digital information. Its effectiveness tends to be more optimal when combined with innovative learning models that are oriented toward Higher-Order Thinking Skills (HOTS). However, the implementation of digital literacy still faces several challenges, such as inconsistent findings across studies, limited infrastructure, disparities in students' digital competencies, and variations in teachers' proficiency. These conditions indicate that the success of digital literacy integration is highly dependent on the quality of instructional design and the readiness of the educational ecosystem. Therefore, strengthening pedagogical practices, enhancing teacher competence, and ensuring sustainable systemic support are essential to optimize the role of digital literacy in transforming biology education into a more adaptive and critical learning environment.

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