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Digital Literacy in Indonesian Biology Education (2020–2025): A Research Synthesis Over One Lustrun, Methodological Critique, and Strategic Roadmap

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Abstract: This study systematically reviews Indonesian research on digital literacy in biology education published from 2020 to mid-2025. Using content analysis, 50 peer-reviewed articles from 17 nationally accredited biology education journals (SINTA-indexed) were examined. The findings reveal a sharp increase in publications in 2023 due to post-pandemic digital adaptation, followed by a moderate decline linked to national policy changes. Quantitative (46%) and research and development studies (42%) dominate, mainly employing static-group quasi-experimental designs. Participants are concentrated at the senior high school level (Grade 10), with underrepresentation of junior high school students, university students, and teachers. Thematically, most studies focus on biodiversity, while advanced topics like molecular biology remain underexplored. Methodologically, the use of questionnaires (70%) is prevalent, with limited adoption of interviews, observations, or test-based assessments. Descriptive statistics are primarily used, with minimal application of inferential methods such as t-tests or ANOVA. Methodological inconsistencies further hinder study replication. The study recommends diversifying research designs, expanding participant profiles, standardizing instructional terminology, and applying more rigorous analysis frameworks to support equitable and digitally adaptive biology education aligned with the Merdeka Curriculum and 21st-century competencies.

Keywords: Biology education; Digital literacy; Systematic review

Introduction

The advancement of information and communication technologies (ICT) has significantly transformed various dimensions of life, particularly education. In the digital era, digital literacy has become a critical competency for students. According to the United Nations Educational, Scientific and Cultural Organization (UNESCO, 2023), digital literacy is defined as the ability to use digital technologies confidently and critically to access, evaluate, create, and communicate information. Within educational contexts, digital literacy serves as a foundational element for 21st-century learning, which emphasizes higher-order thinking and problem-solving skills—competencies that are explicitly embedded in Indonesia's Merdeka Curriculum (Direktorat Jenderal Pendidikan Tinggi, 2020).

Digital literacy extends beyond basic computer skills to include the ability to interact with digital content effectively (Kailani et al., 2021; Aulia, 2020). It involves a range of cognitive and social skills required to navigate and thrive in an increasingly digital landscape (Cruz, 2023; Pepito & Acledan, 2022). Integrating digital

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literacy across all educational levels, from primary to higher education, reflects the evolving nature of learning environments shaped by technological advancement (Saleh & Solihin, 2023; Risamasu et al., 2025).

As a scientific discipline, biology education emphasizes observation, exploration, and analysis of natural phenomena. The integration of digital technologies in biology classrooms creates new opportunities to enhance learning experiences, improve access to information, and deepen students' understanding of abstract or complex concepts. For instance, Satriya et al. (2024) demonstrated that virtual reality (VR) designed using a Problem-Based Learning (PBL) model significantly enhanced both digital literacy and critical thinking skills among biology students. Similarly, the WE-ARe model has proven effective in improving the digital literacy of preservice biology teachers, positively impacting their academic performance (Amin et al., 2023; Helleve et al., 2019). Azzahro et al. (2023) also emphasized the importance of digital literacy in supporting students' cognitive learning outcomes in biology.

Despite these advances, recent studies show that the level of digital literacy among Indonesian biology students remains low. Ananda et al. (2023) and Donovan et al. (2022) reported that high school students in Makassar scored an average of only 37.68% in digital literacy, indicating a low level of proficiency. This finding highlights the urgent need for strategic interventions, particularly in secondary school biology classrooms.

In higher education, although progress has been noted, challenges persist. Rachmatika et al. (2023) and Dominggus et al. (2021) observed that while biology education undergraduates demonstrated strong functional and communication skills, deficiencies remained in creativity, collaboration, critical thinking, and socio-cultural awareness. Halim et al. (2024) and Arjaya et al. (2023) further showed that digital literacy varies widely among students, influencing their ability to benefit from online learning platforms. Ussarn et al. (2022) and Sánchez-Cruzado et al. (2021) echoed this concern, asserting that assessing both current and expected levels of digital literacy is essential for fostering inclusVive, adaptive learning environments.

Several innovative instructional models have been employed to enhance digital literacy in biology education. Pasaribu et al. (2024) and Ayranci et al. (2021) found that using a TPACK-based PBL approach led to a substantial increase in digital literacy, from 10.5% in the pre-cycle to 80.5% in the second cycle. These results affirm the potential of technology-integrated pedagogical frameworks in building digital competencies.

The effective use of digital resources also has broader implications, not only enhancing academic achievement but also fostering critical evaluation of information and increasing student engagement in learning processes (Hafiza et al., 2022; Nawawi & Sari, 2024; Choudhary & Bansal, 2022). Transitioning to digital media is critical, as research indicates that students' ability to navigate digital platforms effectively correlates with improved learning outcomes and knowledge retention (Rini et al., 2022; Johnson & Lark, 2018; Curran et al., 2019).

This shift underscores the need to promote digital literacy among both educators and students in biology education. Students with high digital literacy are better equipped to actively engage with learning materials and independently manage their own learning processes (Rusdi et al., 2023; Halim et al., 2024). Internationally, the integration of advanced tools like augmented reality (AR) has been shown to enhance student engagement and understanding of biological concepts (Arbuzova et al., 2023; Muthaiyah et al., 2021). Sumatokhin et al. (2020) and Risamasu et al. (2025) used the SAMR model to demonstrate how digital tools can transform educational experiences from basic substitution to complete redefinition.

Further supporting this paradigm, Akhyar et al. (2021) and Yusuf et al. (2022) found that digital literacy significantly contributes to students' academic success in online learning, especially during the COVID-19 pandemic. Situmorang et al. (2024) and Zainal et al. (2022) also highlighted the role of gamification and digital game-based learning (DGBL) in improving student engagement and conceptual understanding in biology classrooms.

Despite its growing importance, few studies have systematically mapped how digital literacy is addressed in biology education research published in Indonesian scholarly journals. Such mapping is crucial to understanding the evolving educational paradigm in response to technological changes. This study addresses this gap by conducting a systematic review of digital literacy research trends in national biology education journals.

The study focuses on identifying topic trends, methodological approaches, subject demographics, and educational implications across selected articles. This analysis aims to uncover dominant patterns, emerging theoretical frameworks, and gaps in the literature, offering direction for future research and practical innovation in the field.

Moreover, the urgency of this study is aligned with the Merdeka Curriculum, which emphasizes the development of the Pancasila Student Profile, especially critical and creative thinking. Digital literacy serves as a means to cultivate these traits through the use of

technology—not merely as a tool, but as a medium for processing information and building independent understanding. Digitally enriched biology education is expected to foster awareness of contemporary scientific issues and encourage student engagement in solving environmental problems.

This study also introduces methodological novelty by employing a combined bibliometric and qualitative review approach. Unlike previous conceptual or case-specific studies, this comprehensive method allows for a structured understanding of the development and direction of digital literacy in biology education.

Finally, the study contributes to both general educational science and biology education by mapping current and prospective research themes. These insights are critical for informing policy, guiding curriculum development, and designing teaching strategies that meet the needs of digital-native learners.

In this regard, the study is not only descriptive and analytical but also reflective and prospective. Its findings provide a foundation for further in-depth studies and serve as a reference for developing digital literacy programs in secondary schools and higher education institutions focused on biology education.

Method

Research Design

This study employed a content analysis approach to systematically examine published research findings on digital literacy in the context of Indonesian biology education. The methodological procedure aligns with the framework utilized by Susetyarini & Fauzi (2020), emphasizing the identification of recurring patterns and methodological trends in relevant literature.

Data Sources

The study focused on synthesizing empirical findings from a curated corpus of scientific articles published in SINTA-indexed national biology education journals. A total of 50 peer-reviewed articles, published up to May 15, 2025, were selected from 17 nationally accredited journals. The articles were accessed through the official SINTA portal, hosted by the Ministry of Education, Culture, Research, and Technology of the Republic of Indonesia (https://sinta.kemdikbud.go.id/journals).

To ensure thematic consistency and methodological rigor, inclusion criteria were applied. Articles were included only if they explicitly addressed digital literacy as a primary research variable or as a contextual element in instructional innovation within biology education. This allowed for a robust bibliometric and qualitative synthesis of key trends, including research designs, participant profiles, content topics, instructional treatments, data collection instruments, and analytical techniques.

Research Instrument

The instrument used for data collection and classification was a content analysis guideline, adapted from Susetyarini & Fauzi (2020). This guideline focused on seven analytical dimensions: (1) Year of publication, (2) Type of research, (3) Research subjects, (4) Biology topics studied, (5) Instructional treatments applied, (6) Data collection instruments, and (7) Data analysis techniques.

Table 1. Aspects and Categories Used in Content Analysis in Research

Aspect	Category	
Research Type	A.1-R and D	A.3-Qualitative Research
	A.2-CAR	A4-Quantitative Research
Quantitative Research Types	B.1-Observation Studies (OS)	B.5-True Experimental Designs (TED)
	B.2-Correlational Research (CR)	B.6-Quasi-Experimental Designs (QED)
	B.3-Survey Research (SR)	B.7-Ex Post Facto Designs (EPFD)
	B.4-Pre-Experimental Designs (PED)	
Research Subjects	C.1-VII Grade JHS students	C.7-Undergraduate students
	C.2- VIII Grade JHS students	C.8-Postgraduadate students
	C.3-IX Grade JHS students	C.9-JHS teacher
	C.4-X Grade SHS students	C.10-SHS teacher
	C.5-XI Grade SHS students	C.11- Article
	C.6-XII Grade SHS students	
Data Collection Instruments	D.1-questionnaire sheet	D.4-interview sheet
	D.2-observation sheet	D.5-Validation Sheet
	D.3-test sheet	D.6-Grafik Fry
		D.7-unidentified
Data Analysis Techniques	E.1-mean	E.7-ANCOVA
	E.2-percentage	E.8- Correlation
	E.3-N-gain	E.9-Unidentified
	E.4-t-test	E.10-Others

Aspect	Category
	E.5.Paired
	E.6-ANOVA

Data Analysis

Each article was categorized based on its specific characteristics, aligned with the predefined classification framework. The categorization process involved careful examination of the abstracts, methodology, and discussion sections. This ensured accurate alignment with the analytical categories and maintained internal validity throughout the coding process.

The classified data were then organized and visualized using bar charts, allowing for clear interpretation of research trends and methodological preferences. These visualizations facilitated both descriptive and comparative analyses, revealing insights into the dominance of certain research types, data collection patterns, and thematic concentrations within digital literacy studies in biology education in Indonesia.

Result and Discussion

Findings

Number of Publications

The trend of research publications focusing on digital literacy in Indonesian biology education demonstrates a clear growth pattern.

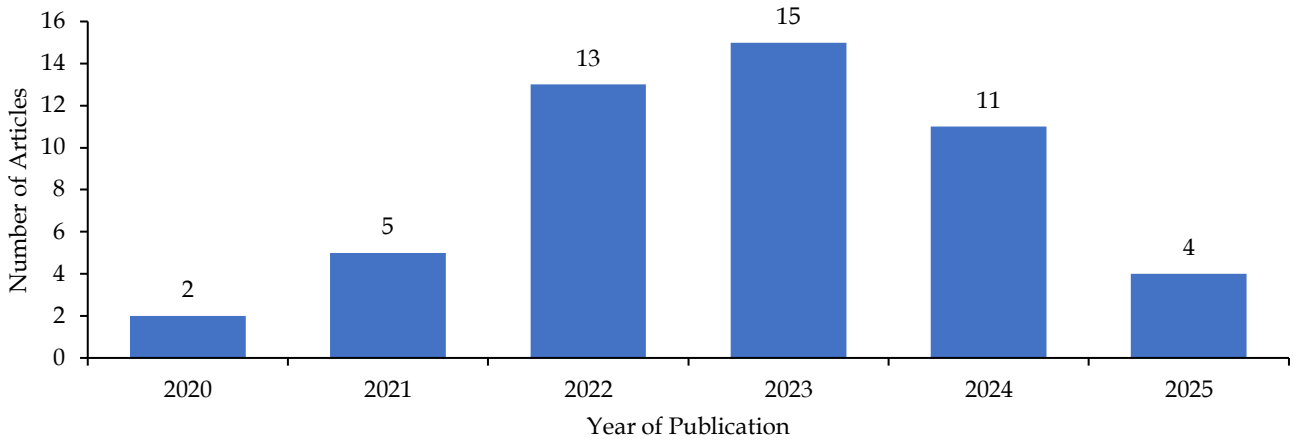

Figure 1. Number of published articles (2020-2025)

As shown in Figure 1, only two articles were published in 2020. This number more than doubled to five in 2021, coinciding with the nationwide shift to online learning during the COVID-19 pandemic, which encouraged educators to explore digital technologies as practical classroom solutions.

The upward trajectory continued sharply, with 13 publications recorded in 2022 and peaking at 15 in 2023—reflecting both increased academic interest and post-pandemic momentum. In 2024, the number slightly declined to 11 articles, likely due to shifting research priorities and tightening publication standards. The figure for 2025 currently stands at four; however, this should be interpreted with caution, as the data only covers the first half of the year. If submission rates remain stable, the total output for 2025 may approach or match that of 2024. A bibliometric study by Risamasu et al. (2025) and Clemmons et al. (2022) affirms this global trend: "Findings show a significant growth in the number of publications, with the highest peak in 2023." Given that domestic publication cycles often intensify in the second semester, the final 2025 count remains open to projection.

Types of Research

Distribution of Research Types in Digital Literacy Studies

The analysis of digital literacy research in biology education journals reveals a dominance of quantitative studies, accounting for 23 out of 50 studies (46%). This is closely followed by research and development (R&D) designs with 21 studies (42%). In contrast, only five studies (10%) employed a qualitative approach, while just one study (2%) used a classroom action research (CAR) design.

These findings indicate a strong preference for empirical, intervention-based methodologies within the field, while reflective and exploratory approaches remain underutilized. This trend suggests the need for broader methodological diversification in future digital literacy research.

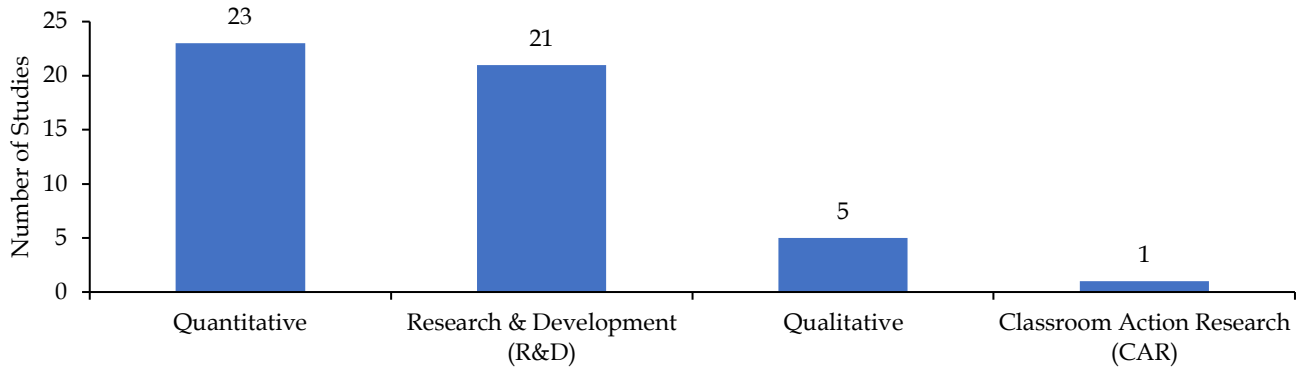

Figure 2. Distribution of research types in digital literacy studies

Quantitative Research Designs

Distribution of Research Subjects in Digital Literacy Studies in Biology Education

The distribution of research designs among quantitative studies on digital literacy in biology education reveals a clear preference for static-group design (SR), which appears in 19 studies (59%). This design compares two non-equivalent groups (e.g., experimental vs. conventional classes) without requiring pre-tests. While efficient in terms of time and implementation, it risks internal validity due to the lack of control over participant equivalence, potentially biasing causal conclusions.

The standard quasi-experimental design (QED), which typically involves pre- and post-tests with non-randomized control groups, was used in 8 studies (25%). This indicates a growing awareness of methodological rigor, although implementation challenges remain, especially in random assignment.

The one-shot case study (OS) appeared in 5 studies (16%), offering simplicity by measuring outcomes after a single treatment on one group. However, the absence of comparison or baseline data reduces its reliability in attributing outcomes solely to digital interventions.

Notably, other designs such as control-group (CR), posttest-equivalent design (PED), true experimental design (TED), ex-post-facto design (EPFD), and meta-analysis were not utilized, highlighting two key issues: limited infrastructure for experimental rigor and gaps in methodological training among biology education researchers.

Future efforts should focus on building capacity through experimental design workshops and encouraging cross-institutional collaboration to improve the validity and generalizability of digital literacy research outcomes.

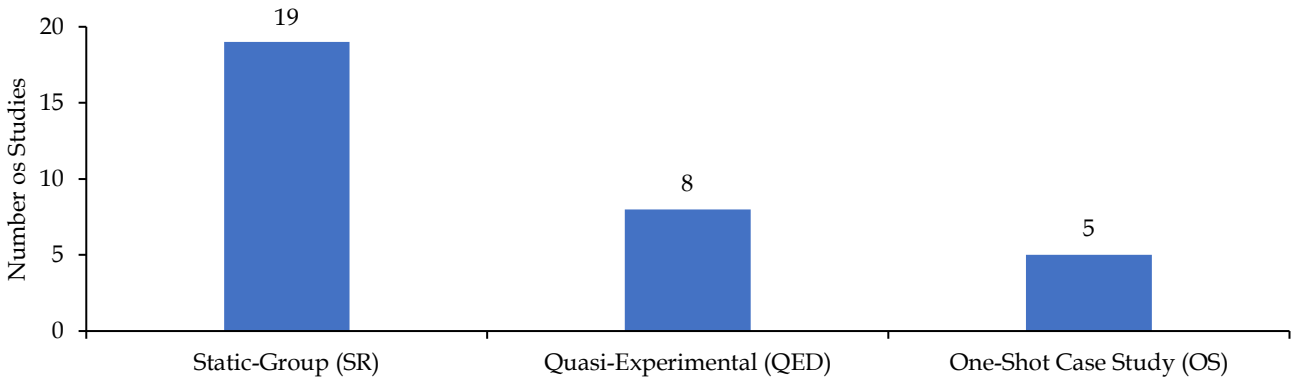

Figure 3. Distribution of quantitative research designs in digital literacy studies

Research Subjects

Distribution of Research Subjects in Digital Literacy Studies in Biology Education

The composition of research subjects in digital literacy studies within Indonesian biology education journals reveals a significant imbalance. As shown in Figure 4, Grade X senior high school students dominate with approximately 24 studies, followed by Grade XI (≈18) and Grade XII (≈10). This pattern indicates a strong research focus on early senior high school learners, particularly as they begin to engage with more complex life science curricula. Grade X is often chosen due to the contextual nature of topics such as biodiversity, ecosystems, and viruses, which are well-suited to digital

instructional tools. Moreover, schools often treat Grade X as a "pilot class" for implementing educational innovations.

In contrast, lower secondary education (junior high) is noticeably underrepresented, with only two studies involving Grade VIII students, and none for Grades VII and IX. This gap may stem from limited ICT infrastructure in rural middle schools or the assumption that digital literacy is less critical at the foundational biology level.

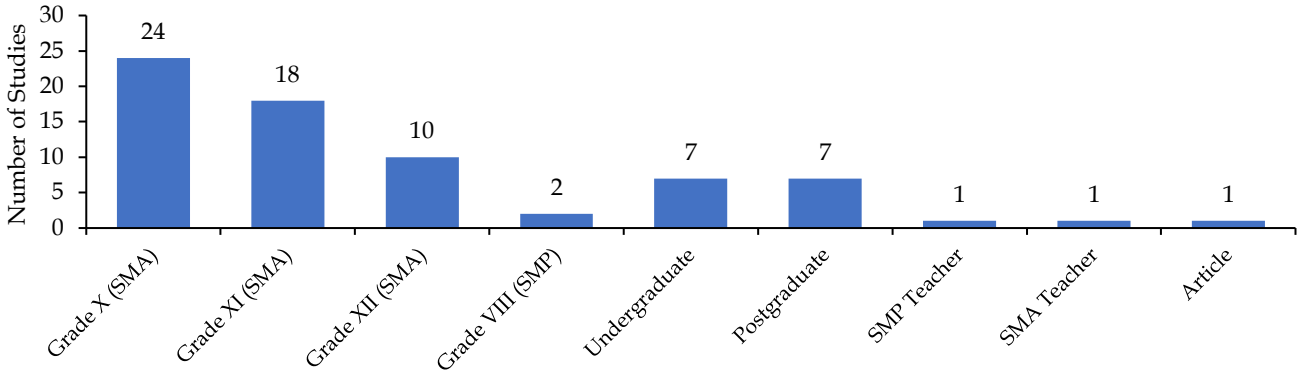

Figure 4. Distribution of research subjects in digital literacy studies

At the higher education level, there are seven studies each involving undergraduate and postgraduate students. These indicate a modest but growing interest in equipping future biology educators and researchers with digital competencies. However, the figures remain small compared to the senior high school cohort, pointing to the need for longitudinal research that examines the continuity of digital literacy development from school through tertiary education.

Interestingly, only one study focused on junior high school teachers, another on senior high teachers, and one used "articles" as non-empirical units of analysis. The scarcity of teacher-based research highlights a missed opportunity to leverage classrooms as laboratories for pedagogical innovation, despite the teacher's critical role in technology integration.

Future research agendas should: (a) Expand samples to include junior high students and teachers. (b) Develop cross-level studies to trace digital literacy progression. (c) Incorporate reflective teacher practices through classroom action research (CAR) to generate relevant and sustainable innovations.

Biology Topics Selected when Conducting Studies

The distribution of biology topics examined in digital literacy studies across Indonesian biology education journals appears diverse yet uneven. A total of 31 articles were analyzed, with "Biodiversity" emerging as the most frequently addressed theme, featured in five studies. The popularity of this topic can be attributed to the abundance of digital resources, such as field visuals, habitat videos, and species identification apps, which make it more accessible for digital integration in learning.

The second most common topic was "Plant Growth and Development", appearing in three studies, followed by several topics that each appeared in two studies, including "Viruses", "Digestion", "Enzymes", "Excretory System", and "Bryophyte Diversity". The focus on viruses is likely influenced by the COVID-19 pandemic, which heightened interest in health-related biological content and its integration with online data sources.

Table 2. Biology Topics Selected when Conducting Studies

Topics	Number of articles
Biotechnology	1
Spermatophyta	1
Viruses	2
Fungi	1
Biodiversity	5
Digestion	2
Cellular Respiration	1
Plant Growth and Development	3
Fern Diversity	1
Enzymes	2
Environmental Changes	1
Excretory System	2
Vertebrate Animals	1
Human Reproductive System	1
Animalis	1
Bryophyta Diversity	2
Circulatory System	1
Botany of Furry Plants	1
Plant Concept	1
Movement System	1

In contrast, 12 topics—such as "Biotechnology", "Fungi", "Spermatophyta", "Vertebrate Animals", and

"Musculoskeletal System"—were each addressed in only one study. This pattern suggests two main trends. First, researchers tend to select content that already has a wealth of digital learning materials available. Consequently, biology topics requiring advanced laboratory equipment or microscopic visualization are often overlooked. Second, there is a noticeable curricular bias: most frequently researched topics are those taught in Grade X, which aligns with the earlier finding that Grade X students dominate the subject pool in digital literacy studies.

This thematic gap presents an opportunity for innovation. Educational developers could: (a) Create multimedia repositories for underrepresented topics such as fungal micrographs or simulations of the circulatory system. (b) Conduct cross-topic comparative studies to examine digital literacy in both macro and micro biological concepts. (c) Involve teachers early in the design process to ensure topic selection aligns with classroom needs and available infrastructure. (d) Develop meta-analyses that synthesize digital literacy impacts across various biological domains.

Moreover, collaborations with conservation institutions or virtual museums could provide authentic digital content that enriches classroom instruction. Such coordinated efforts would not only diversify research themes but also promote equitable access to digital literacy development across the full spectrum of school biology curricula.

Instructional Treatments in Digital Literacy Studies

The distribution of instructional treatments in digital literacy research within biology education reveals a significant dominance of the "Other Models" category, accounting for 13 studies (approximately 81%). This umbrella term typically encompasses a wide range of innovative approaches—such as STEAM-TPACK, augmented reality (AR)-based e-modules, or flipped classrooms combined with educational games which have not yet been standardized within classical instructional model taxonomies.

Table 3. Instructional Treatments in Digital Literacy Studies

Treatment Name	Amount
Another model	13
Not Specific	1
Problem Based Learning	1
Discovery Learning	1

This phenomenon suggests two underlying issues. First, researchers tend to design contextualized strategies tailored to specific school environments, technological resources, and the unique characteristics of biological content. As a result, model names become diverse and non-uniform. Second, it appears that journals lack a consistent classification framework, leading these innovative approaches to be grouped under generalized labels, thereby hindering cross-study meta-analyses and comparisons.

Meanwhile, both Problem-Based Learning (PBL) and Discovery Learning were each used in only one study. Despite their well-documented effectiveness in fostering critical thinking—an essential component of digital literacy—their limited presence may be attributed to several factors: (a) Researchers may consider PBL and Discovery Learning as overstudied, prompting exploration of alternative or hybrid models. (b) Authentic PBL implementation requires extensive face-to-face interaction and complex assessment, which may not align with the limited ICT infrastructure in some schools. (c) There may be a nomenclatural shift, where studies that fundamentally adopt PBL elements are instead labeled as "project-based digital worksheets" and subsequently categorized under "Other Models."

Research Instruments

The distribution of instruments used in digital literacy studies in biology education reveals a strong reliance on questionnaires, which appeared 35 times, accounting for nearly two-thirds of all instruments used. This preference is understandable, as questionnaires offer a quick method for assessing students' perceptions, attitudes, and self-reported digital skills. However, such dominance raises concerns about measurement bias, particularly self-assessment inflation, and may limit insights into the actual learning processes taking place.

The next most frequently used instrument was the validation sheet (12 instances), reflecting the strong presence of research and development (R&D) studies, where expert judgment is required before digital products are trialed. However, the number of validation sheets reported is still lower than the total R&D studies identified earlier, suggesting that some studies may not have explicitly reported their validation processes.

Test sheets (9 times) and interviews (4 times) suggest that cognitive evaluation and qualitative exploration are beginning to be adopted, though they are still not prioritized. Ironically, interviews—despite offering rich contextual insights—are underutilized, even though they can reveal students' motivations, engagement with digital tools, or access barriers.

Observation sheets and Fry readability graphs appeared only sporadically (2 and 1 instances, respectively). Meanwhile, the "unidentified" category (14 instances) indicates a lack of transparent reporting—where instruments are referenced vaguely as "sheets" without further specification, reducing the replicability of findings.

Moving forward, methodological reporting standards should be improved—possibly through mandatory instrument checklists in manuscript submissions. Additionally, the use of multi-method approaches—such as combining questionnaires, observations, and interviews—should be encouraged to triangulate data on what students say, do, and achieve. Diversifying instruments not only enriches the data but also enhances the validity of findings, making digital literacy recommendations more reliable.

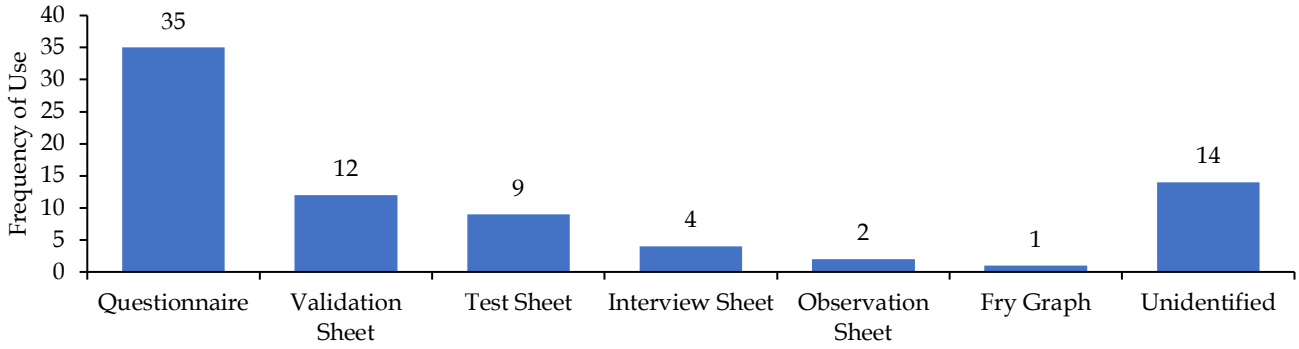

Figure 5. Distribution of research instrumens in digital literacy studies

Data Analysis Techniques

The distribution of analytical methods in digital literacy research in biology education shows a pronounced reliance on descriptive statistics. The two most frequently used techniques—mean and percentage—were each applied in approximately 31 studies, accounting for more than half of all reported analyses. This trend is common as researchers aim to quickly capture patterns in students' digital literacy scores, media acceptance, or intervention outcomes without needing to meet the assumptions required by more complex statistical procedures.

However, this descriptive dominance carries limitations. Conclusions are often restricted to statements like "the average score increased," without substantiating the findings with statistical significance tests or effect size estimates.

A modest shift toward inferential statistics is evident in the use of N-Gain (≈5 studies), which measures relative improvement; t-tests (≈4 studies), which assess differences between groups; and ANOVA/ANCOVA (≈5 studies), used to analyze variance and control for covariates. These methods signal a growing interest in more rigorous evaluation, though their usage remains limited relative to the high number of quantitative and R&D-based studies.

Correlation analysis, which could reveal relationships between variables such as digital media usage, motivation, and learning outcomes, was employed only once—highlighting an underutilized method in this context.

Furthermore, categories such as "Unidentified" (≈7 cases) and "Others" (≈3 cases) reveal shortcomings in methodological reporting, where researchers vaguely describe data analysis as "appropriate methods" without specificity. This practice reduces transparency, hampers replication, and complicates systematic reviews or meta-analyses.

To address these issues, the following strategic directions are recommended: (a) Enhance researchers' statistical literacy through advanced training on effect size measurement, mixed linear models, and path analysis. (b) Standardize methodological reporting in journal submissions by requiring disclosures on statistical software, assumptions, and rationale for choosing specific tests. (c) Diversify analytical approaches by incorporating non-parametric statistics or learning analytics to leverage user-generated log data.

Discussion

The findings of this systematic review reveal a dynamic yet uneven landscape in digital literacy research within Indonesian biology education during the 2020–2025 period. The post-pandemic surge in publications, peaking in 2023, reflects increased scholarly interest and policy-driven motivation to explore the intersection of digital competencies and science education. This temporal pattern aligns with broader global trends, where digital learning gained prominence due to remote learning mandates and 21st-century skills-oriented curriculum reforms (Risamasu et al., 2025; Arbuzova et al., 2023).

The subsequent decline in publication volume does not necessarily indicate a depletion of ideas but likely reflects two converging dynamics. First, journal selectivity has increased following the initial expansion phase, leading to stricter methodological standards and reduced acceptance rates. Second, some researchers have shifted focus toward artificial intelligence, as evidenced in a bibliometric study (Puspitawati et al.,

2024; Andrade et al., 2020) noting the growing interest in the convergence of "Artificial Intelligence," "Human," and "Biology"—a trend that may not be classified under traditional digital literacy research, thus lowering its apparent output.

Despite this growth, methodological concentration and sample homogeneity present challenges to the generalizability and resilience of the current research base. The dominance of quantitative methods (46%) and R&D approaches (42%) indicates a strong emphasis on intervention-based and product-development studies. While such methods are effective for assessing the impact and feasibility of innovations—such as TPACK-oriented PBL or digital worksheets (Pasaribu & Sari 2024)—they often lack the contextual depth afforded by qualitative or mixed-method approaches. This imbalance restricts nuanced understanding of learner experiences and overlooks systemic barriers to digital integration, such as infrastructure limitations and teacher digital competencies.

The reliance on quasi-experimental designs, particularly static group comparisons, further raises concerns about internal validity. These designs are convenient but fail to adequately control for baseline equivalence, resulting in potentially confounded outcomes. The absence of true experimental or longitudinal designs limits causal inference and hinders insights into the developmental trajectory of digital literacy over time. Future research should thus prioritize methodological diversification, including meta-analyses, longitudinal tracking, and in-depth qualitative case studies.

Subject-wise, there is a stark overrepresentation of senior high school students, especially those in Grade X, who account for nearly half of all study participants. In contrast, junior high students, in-service teachers, and preservice educators receive minimal attention. While this focus may be practical due to curriculum structures and resource availability, it neglects the importance of cultivating digital literacy from earlier educational stages and the pivotal role of teachers as digital facilitators. Teacher-led digital pedagogy studies and cross-level comparisons could bridge these gaps and offer a more comprehensive view of literacy progression.

Further thematic analysis reveals a curricular bias in topic selection. Easily digitized content such as biodiversity and plant growth dominates, while complex topics like molecular biology, physiology, and biotechnology remain underexplored. This reflects both content availability and the technical complexity of certain subjects. However, such a narrow thematic focus limits the scope of digital literacy application and marginalizes higher-order scientific content. Addressing this requires the development of digital resources tailored to complex biological phenomena and interdisciplinary themes.

Another pressing issue is the overreliance on questionnaires, used in 70% of the studies as the primary data collection instrument. While practical for measuring self-reported skills and perceptions, questionnaires often lack objectivity and depth. Underutilized instruments such as interviews, observations, and test-based assessments offer triangulated and context-rich insights but are infrequently applied. Additionally, inconsistent reporting of instruments and analytical procedures—with many studies labeled as "unidentified"—impedes replication and systematic synthesis.

Statistically, the field remains dominated by descriptive techniques such as mean and percentage, with limited application of inferential methods like ANOVA, ANCOVA, or correlation analysis. This indicates minimal engagement with advanced statistical modeling that could uncover deeper patterns or account for covariates. The absence of effect size reporting, model validation, and software transparency further weakens analytical rigor. Therefore, enhancing researcher capacity through statistical literacy training and analytic software proficiency is crucial for improving result quality and reliability.

Overall, this review underscores a dual imperative: consolidating gains made in digital literacy research while addressing foundational methodological and thematic gaps. This entails expanding participant populations, enriching methodological frameworks, diversifying biological content coverage, and strengthening both instrument design and data analysis. As the Merdeka Curriculum continues to be implemented, a robust and diversified evidence base will be essential to inform curriculum planning, digital pedagogical strategies, and equitable access policies. A more comprehensive and methodologically pluralistic research ecosystem is vital for cultivating digitally competent generations capable of engaging with complex scientific and societal challenges.

Conclusion

This study mapped 50 peer-reviewed articles published between 2020 and mid-2025 on digital literacy in Indonesian biology education. Academic interest in the topic surged following the COVID-19 pandemic, peaking in 2023—an increase aligned with the implementation of the Merdeka Curriculum and enhanced research funding. However, thematic and methodological scopes remain narrow: the majority of studies utilized quantitative R&D approaches, predominantly featuring static-group quasi-experimental designs, focusing on Grade X students and

biodiversity topics. Data collection was largely limited to questionnaires, and data analysis relied heavily on descriptive statistics, resulting in weak inferential power and limited replicability. These patterns highlight the urgent need for methodological diversification, including the adoption of qualitative methods, inferential statistics, and longitudinal research designs. Future studies should also broaden participant representation across educational levels and standardize the nomenclature used for digital pedagogical models. Strengthening statistical literacy and transparent methodological reporting is equally essential to enhance research quality and reliability. Through these measures, digital literacy research can more effectively contribute to developing Indonesian learners who are scientifically literate, critically minded, and digitally proficient.

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Author Contributions
N.M.: conceptualized the research, research procedures, analyzed the data and wrote the article; A., H.H., R.T., N.: supervised the writing of the article, reviewed and validated the research instruments used.

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Conflicts of Interest
The authors declare no conflict of interest.

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