

Article

Unlocking Scientific Literacy: The Role of E-Modules and Learning Applications in South African Grade 11 Life Sciences Classrooms

Mahlogonolo Innocentia Thobejane, Moses Sibusiso Mtshali * and Mmapake Florence Masha

Department of Mathematics, Science and Technology Education, University of Limpopo, Private Bag X1106, Sovenga 0727, South Africa; 201514113@myturf.ul.ac.za (M.I.T.)

* Correspondence: sibusiso.mtshali@ul.ac.za

Abstract

This study examined the role of e-modules and learning applications in enhancing scientific literacy among Grade 11 Life Sciences learners in a South African secondary school. Grounded in constructivist and connectivist learning theories, the research responded to persistent challenges in learners' conceptual understanding, scientific reasoning, and application of scientific knowledge. A mixed-methods case study design was employed, combining quantitative pre- and post-test data with qualitative classroom observations and semi-structured learner interviews. Thirty learners participated in a technology-enhanced instructional intervention using curriculum-aligned e-modules delivered through Binogi and Google Classroom. Quantitative findings revealed a statistically significant improvement in scientific literacy following the intervention. Learners' mean scores increased from 39.20% (pre-test) to 63.07% (post-test), representing a gain of 23.87 percentage points. A paired-samples *t*-test confirmed that this improvement was extremely significant ($t(29) = 11.58, p < 0.0001$), with a very large effect size (Cohen's $d = 2.11$). Qualitative findings indicated that learners experienced enhanced engagement, improved conceptual clarity, and greater motivation when using digital learning tools, particularly through visualisations, animations, and self-paced learning. However, persistent difficulties with graph interpretation were also identified. The study concludes that the intentional integration of e-modules and learning applications can substantially enhance scientific literacy in Life Sciences by supporting conceptual understanding, reasoning, and learner engagement. These findings highlight the importance of pedagogically guided digital integration and teacher professional development to strengthen science learning outcomes.

Keywords: scientific literacy; teaching and innovation; E-modules; learning applications; digital technologies

Academic Editor: Regina Jucks

Received: 20 October 2025

Revised: 12 January 2026

Accepted: 13 February 2026

Published: 4 March 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

1.1. Background

Scientific literacy is essential for navigating 21st-century challenges, enabling individuals to make informed decisions, critically evaluate scientific claims, and engage with socio-scientific issues (Wikanta & Susilo, 2022). In Life Sciences education, analytical thinking, conceptual understanding, and problem-solving skills are supported. In this

study, scientific literacy is conceptualised within the context of Grade 11 Life Sciences and refers to learners' ability to demonstrate conceptual understanding of biological concepts, apply biological knowledge to interpret data and solve problems, communicate scientific explanations using appropriate Life Sciences terminology, and relate biological concepts to real-world and societal contexts such as health, biodiversity, and environmental sustainability (OECD, 2023; Jackson et al., 2021). However, many classrooms still rely on rote learning and teacher-centred methods, which limit deeper engagement and critical thinking (Wang, 2022). To address this, digital tools such as e-modules and learning applications offer interactive, personalised learning experiences that can enhance learner understanding (Rahmat et al., 2020). Grade 11 Life Sciences learners in South Africa face particular challenges with abstract topics like genetics and cell division. While the Curriculum and Assessment Policy Statement (CAPS) encourage constructivist, real-life connections in science teaching (Department of Basic Education, 2011), the limited use of inquiry-based methods continues to hinder scientific literacy development (Ma, 2023).

ICT tools featuring simulations, videos, and assessments can help learners visualise difficult concepts and engage in self-directed learning. These digital strategies support learners in applying scientific knowledge across different contexts (Balalle, 2024; Timotheou et al., 2023). Research both globally and locally supports the use of digital tools to enhance scientific literacy, with studies showing improvements in conceptual understanding, inquiry skills, and engagement (Hwang et al., 2021; Joshi et al., 2025). In South Africa, National Senior Certificate (NSC) diagnostic reports for 2020 and 2021 highlighted continued struggles in applying scientific knowledge and reasoning, especially in complex topics. As such, this study responds by exploring how e-modules and learning applications can support scientific literacy in the Capricorn South District's Grade 11 Life Sciences classrooms. By examining reasoning and experiences with digital tools, the research aims to offer insights into how technology can foster deeper understanding, strengthen scientific reasoning and promote inclusive science education. The goal is to empower learners to actively engage in scientific dialogue and decision-making in their communities (Balaban et al., 2023; Simamora et al., 2020).

Operational definition of Scientific Literacy:

In this study, scientific literacy is operationalised using four components aligned with PISA (2022) and Adenle et al. (2023):

- (a) Scientific knowledge—understanding of Life Sciences concepts (e.g., genetics, ecology, cell division);
- (b) Scientific application—applying knowledge to unfamiliar contexts, analysing data, interpreting graphs, and solving problems;
- (c) Scientific communication—explaining scientific ideas clearly using appropriate terminology, constructing conclusions, and responding to written prompts;
- (d) Understanding science in society—recognising how Life Sciences concepts relate to real-world issues.

This operationalisation guided the research design in terms of interview responses, pre- and post-test, classroom observations, and qualitative coding, which are used consistently throughout the article. Additionally, to better understand how e-modules and learning applications can unlock scientific literacy, this research sought to answer the following questions:

RQ1: *How does the use of e-modules and learning applications influence Grade 11 learners' scientific literacy, as defined by scientific knowledge, application, communication, and understanding of science in society?*

RQ2: *What are learners' attitudes and perceptions regarding the use of e-modules and digital learning tools in Life Sciences, particularly in terms of motivation, enjoyment, and perceived usefulness?*

1.2. Importance of Scientific Literacy

In the context of Grade 11 Life Sciences, scientific literacy is defined in this study as the ability of learners to show conceptual grasp of biological concepts, apply biological knowledge to interpret data and solve problems, communicate scientific explanations using appropriate Life Sciences terminology, and relate biological concepts to societal and real-world contexts like environmental sustainability, biodiversity, and health (OECD, 2023; Jackson et al., 2021). In South Africa, despite its emphasis in CAPS and alignment with global benchmarks like PISA (2022), scientific literacy remains inconsistently implemented in classrooms (Rudolph, 2023; Broderick, 2023). Rather than fostering scientifically literate citizens, classroom practices often prioritise rote memorisation and preparation for scientific careers. This foundationalist model limits learners' ability to apply science to real-world challenges and undermines broader educational goals such as critical thinking, ethical reasoning, and informed decision-making (Osborne & Allchin, 2024, Jackson et al., 2021).

1.3. Factors Affecting the Unlocking of Scientific Literacy in Grade 11

Challenges to effective implementation include passive teaching methods, poor learner motivation, under-resourced schools, and significant language barriers, particularly in multilingual South African classrooms (Olivier & Kruger, 2022). Learning Life Sciences through a second language may hinder comprehension when learners are required to process abstract scientific terminology, interpret symbolic representations, and articulate explanations using unfamiliar academic language. This linguistic load can reduce cognitive resources available for conceptual understanding and scientific reasoning, particularly in multilingual classrooms (Valladares, 2021). However, language alone does not determine learning outcomes. Effective learning also depends on the quality of curriculum design and instructional alignment. When digital learning tools are poorly aligned with curricular goals or lack pedagogical scaffolding, they may result in superficial engagement rather than deep understanding (Stevenson et al., 2020). Therefore, this study emphasises not only teacher training and alignment with curriculum objectives, but also the use of carefully designed, curriculum-aligned digital resources that support conceptual progression, visualisation, and reflective learning.

1.4. Impacts of ICT Tools on Unlocking Scientific Literacy

The recent literature advocates for learner-centred, inquiry-based pedagogy supported by digital learning tools as a practical solution to these challenges (Suwono et al., 2021; Valladares, 2021). E-modules and learning applications have shown potential to enhance learner engagement, comprehension, and inclusivity by offering interactive, multi-modal content tailored to diverse learning needs (Mikić et al., 2025).

These tools can support constructivist approaches, enabling learners to build knowledge actively through exploration, dialogue, and contextual learning (Kaldaras et al., 2024). Furthermore, integrating language and science instruction through digital platforms can bridge linguistic gaps and support foundational literacy skills, which are essential for scientific engagement (Dini et al., 2024). The ICT in science education is underscored by global studies, highlighting its role in enhancing inquiry, problem-solving, and motivation (Abdurrahman, 2022; Reginald, 2023). Models such as Interactive Socio-Scientific Inquiry (ISSI) illustrate how digital tools can connect scientific content to real-world issues, promoting critical thinking and societal relevance (Arizen & Suhartini, 2019).

However, these benefits are dependent on equitable access, sustained teacher professional development, and intentional pedagogical integration (Khazanchi et al., 2022). Without these supports, digital tools risk becoming underutilised or superficially applied, limiting their educational value. In the South African context, digital interventions must address systemic inequities and be aligned with curriculum goals and contextual realities to support scientific literacy meaningfully. As Balalle (2024) and Adenle et al. (2023) argue, digital technologies must be coupled not just as delivery mechanisms but as transformative tools embedded in reflective and inclusive pedagogies. The integration of e-modules and learning applications in Grade 11 Life Sciences classrooms presents a promising pathway to close the gap between educational policy and practice, fostering learners who are not only academically competent but also scientifically literate citizens equipped for the demands of the 21st century.

2. Materials and Methods

This study adopted a mixed-methods case study design, integrating qualitative and quantitative data to obtain a comprehensive understanding of how digital learning tools influence Grade 11 learners' scientific literacy. The mixed-methods approach was justified because the intervention aimed to measure both changes in learner performance (quantitative) and shifts in learner perceptions, engagement, and experiences (qualitative). Quantitative pre- and post-test scores provided evidence of learning gains, while qualitative interview data illuminated the mechanisms underlying these gains. This form of complementarity is consistent with contemporary educational research, which argues that digital learning interventions require both performance data and learner perspectives to be meaningfully interpreted (Creswell & Creswell, 2023; Johnson & Onwuegbuzie, 2004).

Quantitative data from the pre- and post-tests were analysed using descriptive statistics (percentage marks improvement) and inferential statistics (paired *t*-test). Descriptive trends were used to identify performance shifts attributable to the digital intervention. Furthermore, the findings were integrated with qualitative themes during interpretation through a triangulation strategy, where pre/post results were cross-checked with interview insights and classroom observations to validate patterns emerging across data sources.

The selection of a single-class case study was intentional, as this design allows for an in-depth exploration of educational interventions within their authentic contexts. Case studies are particularly valuable when examining complex classroom realities where factors such as digital access, school culture, and learner dynamics significantly shape learning processes and outcomes (Yin, 2024). The participating class reflected a typical Life Sciences cohort within a rural South African school, providing a representative context for understanding how digital learning tools operate in environments characterised by lack of resources and uneven technological access.

2.1. Informing Theories of the Research

This study is grounded in constructivist and connectivist learning theories, both of which support active, learner-centred approaches to developing scientific literacy through digital tools. Constructivism emphasises that learners build knowledge by actively engaging with content, reflecting on experiences, and interacting with peers and their environment (Hein, 2007; McLeod, 2019). In this study, tools like Binogi and Google Classroom enabled learners to shift from passive receivers to active participants by watching interactive videos, engaging in self-assessments, and applying content in varied contexts (Schwan & Cress, 2020; Mayer, 2024). Key tenets of constructivism, such as learning through experience, developing metacognitive skills, and the importance of motivation, were evident in observations, interviews, and tests. Learners showed greater engagement

and understanding when lessons were designed to be interactive, visually rich, and relevant to their experiences (Filgona et al., 2020; Liu et al., 2024). Connectivism complements this by highlighting how digital technologies extend learning beyond the classroom (Goldie, 2016).

Learners accessed diverse information sources, evaluated credibility, and used technology to store and retrieve knowledge (Afroz Alam, 2023). These strategies supported learners in making meaningful connections and navigating complex scientific concepts. Together, these theories explain how e-modules and apps support learners' scientific literacy, enhancing their motivation, enjoyment, and perceived usefulness of Life Sciences content while fostering critical thinking, collaboration, and digital competence. The observed improvements in learner performance and engagement aligned with, constructivist learning cycles such as personal meaning-making and active processing and connectivist processes such as leveraging networks, multimedia pathways, and peer interaction.

2.2. Context of the Study

This study was conducted within a Grade 11 Life Sciences classroom at a secondary school in the Mamabolo Circuit, Capricorn South District, Limpopo Province, South Africa. Ethics approval for this site was granted by the Limpopo Department of Education, Mamabolo Circuit and the school. The research responds to ongoing challenges within the South African education system related to learners' scientific literacy, particularly within Life Sciences. Despite the national curriculum (CAPS) emphasising scientific reasoning, critical thinking, and real-world application of scientific knowledge (Department of Basic Education, 2011), many learners continue to struggle with mastering complex biological topics such as genetics, meiosis, and evolution (Simamora et al., 2020). These challenges are often compounded by traditional teacher-centred pedagogies that limit active learning and inquiry. In response, this study explores how digital learning tools such as Binogi and Google Classroom can be used to improve scientific literacy among learners by providing more interactive, personalised, and accessible educational experiences.

2.3. Sampling and Participants

A purposive non-probability sampling strategy was used to select 30 Grade 11 Life Sciences learners who had consistent access to the intervention tools (Google Classroom and Binogi). This approach is appropriate for case study research where participants must have direct exposure to the phenomenon under investigation. However, the sample size limits external validity, and findings cannot (Palinkas et al., 2015). Purposeful sampling for qualitative data collection and analysis in mixed method implementation research. However, the sample size limits external validity, and findings cannot be generalised beyond the study context. This limitation is acknowledged explicitly in the Discussion and Limitations sections. Six learners were selected for follow-up semi-structured interviews based on maximum variation (high, moderate, and low performers) to capture a wider range of experiences.

To contextualise the sample, demographic information is as follows:

- (a) Gender: 18 females, 12 males
- (b) Age range: 16–18 years
- (c) Socioeconomic context: The school serves a low- to middle-income community where most learners rely on shared mobile devices and prepaid data bundles.
- (d) Digital access: Approximately 70% reported intermittent internet access, which influenced engagement with the intervention.

2.4. Binogi and Google Classroom Pedagogy

The Binogi intervention consisted of structured, topic-aligned digital learning activities delivered through Binogi and Google Classroom to complement the Grade 11 Life Sciences curriculum. Binogi is a multilingual platform offering short (3–5 min) animated videos, interactive quizzes, and flashcards, enabling learners to visualise complex processes such as meiosis, allele inheritance, and population interactions in their preferred language. For each topic, the teacher assigned curated playlists via Google Classroom, which also functioned as the learning management system for distributing e-modules, assignments, and feedback. During lessons, learners watched animations, completed auto-graded quizzes with instant feedback, and used flashcards to consolidate key terminology, while the platform's badges and streaks helped sustain motivation. Teacher facilitation included modelling platform navigation, prompting note-taking, and leading brief post-video discussions to reinforce understanding. Learners were able to interact with the digital platform at home using English as the primary language of instruction, as there are no additional South African languages available.

2.5. Instruments

To address the research questions and ensure triangulation, the study employed multiple data collection methods, namely, participant observation, where the researcher, who also served as the classroom teacher, observed learners' engagement with digital tools, collaboration patterns, and classroom dynamics. Since the researcher also served as the classroom teacher during the intervention, a structured observation guide (Supplementary Materials S1.1) was employed to enhance consistency and transparency in classroom observations and to minimise, rather than eliminate, potential researcher bias. The guide included predetermined indicators aligned with the research questions and the literature on scientific literacy, such as learner participation, use of scientific language, interaction with digital resources, and teacher facilitation strategies. This immersive approach enabled the researcher to capture rich, real-time insights into how learners engaged with the e-modules, as well as the challenges and successes that emerged during implementation. To reduce subjective interpretation and selective noticing, observations were recorded immediately after lessons and triangulated with interview data and assessment results. Semi-structured interviews conducted with six learners allowed for in-depth exploration of individual experiences with digital learning tools. The semi-structured format ensured alignment with research objectives while allowing flexibility to probe unexpected responses (Galletta, 2013; Kvale & Brinkmann, 2015). Interview responses were audio-recorded and transcribed verbatim.

Document review consisting of pre- and post-test scripts was used to assess changes in learners' understanding of scientific concepts. These criterion-based assessments provided quantitative data on learners' performance before and after the digital intervention (Mahajan & Singh, 2017; Hussain et al., 2015). The tests consisted of items aligned with the CAPS Grade 11 Life Sciences curriculum. Items assessed were: (a) concept recall (multiple choice, terminology matching); (b) diagram interpretation (mitosis/meiosis, ecological graphs); (c) data analysis (tables and graphs from population ecology); (d) scientific reasoning (identifying variables, formulating hypotheses); and (e) application tasks (case-study scenarios). Additionally, item formats included multiple-choice, short answer, data interpretation, and extended reasoning questions. Both tests used the same structure and cognitive levels but different surface features to avoid memorisation effects. Learners were assured that participation or responses during data collection would not influence their academic grading. To minimise the influence of random guessing, the assessment instrument included a combination of multiple-choice, data interpretation, and extended-response items. Multiple-choice questions were designed with plausible distractors

aligned to common misconceptions identified in the Life Sciences curriculum. Data interpretation items required learners to analyse graphs and tables related to biological processes, thereby reducing the likelihood of correct responses through guessing alone.

Content validity was established through alignment with CAPS Life Sciences learning outcomes and prior use of similar assessment structures in scientific literacy research. Construct validity was supported by mapping assessment items to overlapping but distinguishable components of scientific literacy. For example, graph interpretation tasks assessed learners' ability to apply biological knowledge to analyse data, while extended-response items assessed scientific communication by requiring learners to construct coherent explanations using appropriate Life Sciences terminology. Although these components are interconnected, they were operationalised through task demands rather than treated as isolated skills.

2.6. Data Analysis

The study employed thematic analysis to interpret the qualitative data collected from the interviews and observations. This method is appropriate for examining complex phenomena such as learners' experiences with digital tools and their development of scientific literacy (Braun & Clarke, 2019). An inductive approach guided the analysis, allowing themes to emerge from the data without being constrained by pre-conceived categories (Bingham & Witkowsky, 2022). An inductive thematic analysis approach was employed to analyse interview and observation data following Braun and Clarke's (2019) reflexive framework. Initial open coding involved assigning descriptive labels to segments of text, such as visual clarity of animations, difficulty with terminology, and self-paced learning benefits. These codes were then examined for conceptual similarity and collapsed into broader categories based on shared meaning and relevance to the research questions. For example, codes related to visual explanations, repeated exposure, and learner control were grouped under a broader theme of conceptual understanding through digital visualisation. Although coding was conducted manually, the process followed principles similar to those supported by qualitative analysis software such as NVivo. NVivo was not used as a coding method, but rather as a conceptual reference for systematic organisation, comparison, and refinement of codes into themes.

2.7. Limitations

This study was bounded by several limitations that should be considered when interpreting the findings. First, the research was conducted as a single-class case study within one secondary school, which restricts the transferability of the results to other contexts. Learners' experiences, access to technology, and school resources may differ substantially across South African schools, particularly between rural and urban settings. Second, the timeframe of the intervention was limited, providing only a short period for learners to engage with the e-modules and learning applications. A longer intervention might have yielded deeper conceptual gains or provided more opportunities to address persistent challenges, such as graph interpretation. Third, the dual role of the teacher-researcher may have introduced bias, despite attempts to minimise it through observation protocols and triangulation. Additionally, inequalities in digital access and device availability influenced the degree to which learners could fully engage with technology-enhanced activities. These limitations suggest that further research involving multiple schools, longer implementation periods, and varied learner populations is needed to enhance the generalisability of the findings and to explore the sustained impact of ICT on scientific literacy development.

3. Results

RQ1: *How does the use of e-modules and learning applications influence Grade 11 learners' scientific literacy, as defined by scientific knowledge, application, communication, and understanding of science in society?*

3.1. Document Review

For this question, document review is one the data collections tools used in this study, which contained qualitative and quantitative data. The document review in this study consisted of pre- and post-test data.

3.1.1. Quantitative Data

A paired-samples *t*-test (Table 1) was conducted to determine whether the post-test scores differed significantly from the pre-test scores after the intervention. The results show a statistically significant improvement:

Table 1. Paired-Samples *t*-Test Results.

Measure	Value
Mean Difference (%)	23.87
t-value (df = 29)	11.58
<i>p</i> -value	<0.0001
95% CI	19.65 to 28.08
Cohen's d	2.11

The pre-test results in Table 2 showed that learners began with relatively low levels of content mastery, with an average score of 39.20%. After the intervention, which involved using e-modules and digital learning applications, the post-test mean increased substantially to 63.07%. This represents an improvement of 23.87 percentage points. The observed improvement of 23.87 percentage points represents a substantial increase in performance within the context of a short-term classroom intervention. While this gain cannot be interpreted as definitive evidence of long-term learning, the large effect size (Cohen's *d* = 2.11) suggests that the change was not only statistically significant but educationally noteworthy when considered alongside qualitative evidence of improved engagement and conceptual clarity.

Table 2. Pre-test and Post-test Scientific Literacy Scores (*n* = 30).

Statistic	Pre-Test	Post-Test
Mean (%)	39.20	63.07
Standard Deviation	12.96	10.33
Standard Error	2.37	1.89

The statistical analysis confirms that this improvement was not due to random chance. A paired-samples *t*-test showed an extremely significant difference between pre- and post-test scores ($t(29) = 11.58, p < 0.0001$). The 95% confidence interval (19.65 to 28.08) further demonstrates that the true average improvement is both large and precise. The relatively small standard error of the difference (2.060) shows consistency in how learners benefited from the intervention. The findings provide strong evidence that the use of e-modules and digital learning applications had a substantial and reliable positive effect on learner performance. The results suggest that integrating these tools into Life Sciences instruction can significantly enhance students' conceptual understanding and achievement.

Effect size calculations indicated that the intervention had a very large impact on scientific literacy performance. A Cohen's *d* value of 2.11 was obtained, which reflects an extremely large effect according to conventional benchmarks. This suggests that the observed improvement (23.87 percentage points) was not only statistically significant but also educationally meaningful. Although a randomised control group was not feasible within the school context, a quasi-comparative analysis was conducted using historical cohort data. The previous two Grade 11 cohorts (taught using traditional methods) demonstrated average pre–post improvements of 5–8 percentage points on similar teacher-developed assessments. In contrast, the current cohort improved by 23.87 percentage points, representing a substantially larger gain.

Additionally, term test averages for the non-participating Grade 11 class during the same period increased only marginally (3.5 percentage points). While not a true experimental control, this comparative evidence strengthens the argument that the digital intervention contributed meaningfully to the observed gains.

Additionally, in support to the above-mentioned, the table below shows learners' competence improvement of the pre- and post-test.

Table 3 below shows the analysis of learner performance based on the pre- and post-test results demonstrates a marked improvement in competence levels following the intervention. Prior to the intervention, eight learners failed to meet the National Senior Certificate (NSC) minimum pass requirement of 30%, highlighting substantial gaps in scientific literacy. Following exposure to the e-modules and digital learning applications, all eight learners showed notable improvement, aligning with the overall upward shift in class performance.

Table 3. Summary for comparison of pre- and post-test competence levels.

	PRE-TEST	POST-TEST
Competence Level	Number of Learners	
0–29	8	0
30–39	7	1
40–49	9	2
50–59	4	3
60–69	1	13
70–79	1	9
80–100	0	1

This improvement is supported by qualitative evidence from learner scripts: pre-test responses revealed difficulties with terminology recall, applying scientific information to questions, identifying independent and dependent variables, formulating hypotheses, and interpreting population graphs. In contrast, post-test scripts demonstrated clearer and more accurate explanations of graph trends, improved hypothesis formulation, and enhanced recall and application of scientific concepts across different contexts. See Supplementary Materials S1.5. Although significant learning gains were observed, these improvements cannot be attributed solely to the digital intervention. Factors such as peer discussion, repeated exposure to content, and learning outside the classroom may also have contributed to performance gains. Furthermore, the absence of a control group limits causal inference. The findings should therefore be interpreted as indicative rather than conclusive evidence of the effectiveness of e-modules in enhancing scientific literacy.

3.1.2. Qualitative Data

Pre-Test

The document review revealed that Grade 11 Life Sciences learners demonstrated generally low levels of scientific literacy, particularly in areas requiring the application of cognitive skills such as interpretation, analysis, and problem-solving. Learners struggled to recall basic concepts and terminology and showed limited ability to interpret scientific diagrams and graphs, analyse tables, and apply learned knowledge to unfamiliar contexts, which are key competencies outlined in the Life Sciences CAPS document. Although some improvement was noted in questions involving diagram interpretation, learners consistently underperformed in graph-based and calculation tasks, such as those involving the mark and recapture method in population ecology. These findings highlight the limitations of traditional, teacher-centred instruction, which often emphasises rote memorisation over conceptual understanding. The inability of learners to apply scientific knowledge in different formats and contexts underscores a critical gap in their scientific literacy. This supports the need for interactive and technology-enhanced learning approaches, such as e-modules and learning applications, to promote deeper conceptual understanding and cognitive engagement aligned with the goals of scientific literacy.

Post-Test

The results of the study revealed that the use of e-modules and learning applications such as Binogi and Google Classroom significantly enhanced Grade 11 learners' scientific literacy in Life Sciences. Following the intervention, learners demonstrated improved conceptual understanding, problem-solving, and critical thinking skills across various cognitive levels. Post-test performance showed notable gains in answering low-order questions (e.g., multiple choice, term identification, diagram interpretation) as well as higher-order tasks involving scenario analysis, experimental reasoning, and graph interpretation. Learners increasingly applied scientific knowledge in unfamiliar contexts, interpreted data, and constructed evidence-based arguments, reflecting growth in key aspects of scientific literacy. While challenges remained, particularly in distinguishing between concepts like "aim" and "hypothesis," and in interpreting graph trends, the integration of ICT tools fostered greater engagement, independent learning, and improved communication of scientific ideas. These outcomes support the potential of e-modules and learning applications to address curriculum goals outlined in CAPS and equip learners with the cognitive and analytical skills required for scientific literacy and successful assessment performance.

These shifts reflect the impact of technology-enabled pedagogical tools, such as Binogi and Google classroom, which provided interactive explanations, scaffolded practice, and continuous formative feedback. Together, the quantitative and qualitative data suggest that deliberate integration of digital resources can effectively strengthen conceptual understanding, support inquiry skills, and reduce performance disparities within the Life Sciences curriculum.

3.2. Interview Data

The interview responses revealed that learners overwhelmingly preferred learning Life Sciences through ICT tools such as Google Classroom and the Binogi app over traditional methods. Learners reported that these digital platforms enhanced their understanding by providing visual aids, simulations, and real-time feedback, which made abstract concepts more accessible and engaging. Many highlighted that visuals and interactive videos significantly improved recall, comprehension, and overall academic performance. Additionally, learners expressed a strong desire to see more technology integration in

their classrooms, such as the use of projectors and more frequent ICT-based lessons, citing better engagement and deeper learning. However, despite these benefits, challenges remained in reading, writing, and especially communicating scientific language. Learners struggled with scientific terminology, pronunciation, and the ability to articulate scientific concepts in assessments and discussions. These difficulties indicate gaps in scientific literacy, particularly in scientific communication and conceptual application. Overall, the results suggest that while e-modules and learning applications enhance conceptual understanding and motivation, their full potential in developing scientific literacy depends on addressing language and communication barriers.

RQ2: *What are learners' attitudes and perceptions regarding the use of e-modules and digital learning tools in Life Sciences, particularly in terms of motivation, enjoyment, and perceived usefulness?*

3.3. Classroom Observations

Classroom observations revealed that the use of e-modules and digital learning applications significantly enhanced learners' engagement, motivation, and development of scientific literacy in Grade 11 Life Sciences. Learners were more attentive and focused during ICT-integrated lessons compared to traditional instruction, showing enthusiastic participation and a clear preference for technology-enhanced teaching. Tools such as the Binogi app and Google Classroom positively influenced learners' attitudes toward Life Sciences, increasing their motivation, enjoyment, and perceived usefulness of the subject. Learners demonstrated an improved understanding of scientific concepts, applied knowledge in various contexts, and showed growth in critical thinking, problem-solving, communication, and collaboration, which are core components of scientific literacy. The digital tools also sparked curiosity and sustained interest in Life Sciences, with learners expressing a desire for continued ICT use in future lessons. Despite these benefits, the limited accessibility to platforms like Google Classroom underscored existing equity challenges in implementing digital learning tools across all learners.

During the lessons, several learners leaned forward as the animation showed various scientific concepts. Two learners spontaneously began debating the predicted outcomes of a on how organisms interact with the resources competing for resources displayed in the video. However, another group whispered that their device "kept restarting," illustrating the unevenness of digital access. Such varied observations demonstrate the complexity of implementing ICT in resource-constrained environments.

3.4. Interviews

The interviews revealed that Grade 11 learners' prior intervention possessed a basic understanding of Life Sciences, but overall scientific literacy remained low, this was evidenced by their difficulties with investigative questions, scientific terminology, and conceptual explanations. Basic understanding in this study refers to correct recall of concepts and accurate interpretation of diagrams, while low scientific literacy refers to limited ability to apply knowledge, analyse graphs, or construct evidence-based explanations criteria drawn from the study's operational definition. Learners reported challenges in reading, writing, and communicating scientific information due to complex language, lack of practical exposure, and limited conceptual understanding. However, the integration of e-modules and digital tools, specifically the Binogi learning application, was perceived as highly effective in enhancing motivation, enjoyment, and perceived usefulness in learning Life Sciences. Learners highlighted that the visual and interactive nature of Binogi videos improved their understanding, recall, and ability to apply scientific concepts in real-life contexts. Furthermore, the digital content increased learner engagement, sustained attention, and facilitated clearer comprehension of abstract concepts, suggesting that digital

learning tools are valuable in promoting scientific literacy in Life Sciences education. The above-mentioned is supported by the responses learners provided below:

- Which method do you prefer to use to learn Life Sciences: Traditional or ICT applications such as Google classroom, and Binogi?

LSA, LSC, LSE and LSF: I prefer using ICT (Google classroom and Binogi).

LSB: I prefer the use of ICT because many learners, including myself, are comfortable using our mobile phones and may not always feel confident participating in class discussions. Learning through videos is helpful. I have used different digital learning applications, and they have helped me too much, as I was able to improve my performance using them.

LSD: I prefer learning through Binogi and Google Classroom because Binogi presents terms using different approaches and show how questions are asked and answered. The use of images and videos helps me see and understand terms more clearly than traditional teaching methods, where the teacher writes on the board and reads directly from the textbook.

- Which type of question in Life Sciences assessments do you find difficult and why?

LSA: I find investigative questions difficult because they need answers based on observations and understanding of Life Sciences. Although I can see what is presented, I struggle to explain my answers thoroughly using science language. Again, I find it difficult to identify the hypothesis and the aim of the investigation when responding to these types of questions.

LSB: For me, I would say the question where we need to explain some terms and processes.

LSC: I find investigative questions difficult, especially those related to micro-organisms, because they involve different scientific terms that are challenging to use correctly. For example, when learning about the growth of *E. coli*, we are unable to conduct experiments at school due to a lack of appropriate equipment. As a result, we struggle to answer questions about its shape and growth because we have never observed it directly.

LSD: The most difficult questions for me are those that need labelling diagrams. I struggle to remember all the correct labels and the appropriate science names.

LSE: I struggle with writing biological terms because of spellings, and it is hard for me to read and write those terms.

LSF: Writing biological terms, because I struggle with spellings, which results in difficulty writing those terms.

- Is the use of learning applications (Google Classroom and Binogi) effective in learning Life Sciences? Elaborate how.

LSA: Yes, it is effective because it allows me to see things that cannot be visualised with the naked eye. For example, in the chapter on tissues and cells when reading from textbook, I cannot see tissues and cells directly, but the Binogi app can display and explain them on the projector.

LSB: Yes, it is effective. Although I used Binogi for only a short time, I noticed a huge difference compared to learning from a book. I found learning with the app much more effective and engaging.

LSC: Yes, it is effective because it uses animations that we can connect with. Learning visually helps me remember the concepts better than just reading from a textbook.

LSD: Yes, because the visual images make learning enjoyable and increase my passion and concentration during the lesson. For example, in the topic of gaseous exchange, I could see exactly how it happens rather than just reading about it in the book.

LSE: Yes, I think it is very effective because it helps us think critically and logically.

LSF: Yes, it is effective. While learning through Binogi, I was able to understand the concepts better and apply them in real-life situations. Since Binogi uses videos to show how Life Sciences concepts apply in the environment, I can now observe these concepts in real life. For example, if I see a bird on a flower, I recognise it as a mutualistic symbiotic relationship. Similarly, if I see a bird near a goat looking for food, I understand that as commensalism.

- Did the Binogi digital videos used in class improve your Life Sciences knowledge? Explain how.

LSA: Yes, it did, because when I was asked some questions, I was able to understand what they meant. With traditional teaching, I struggled to visualise the terms as clearly as I am doing with the Binogi app. Binogi allowed me to see the terms as they were presented in real contexts, which made me feel confident and able to answer the questions successfully.

LSB: Yes, because initially when the teacher was teaching using textbook, I would end up losing focus, as I am having a short concentration span and learn nothing. However, since Binogi uses cartoons which are fun and interesting to watch, they helped me to focus in class which led me to understand better what was taught.

LSC: Yes, there were difficult concepts in Life Sciences that I only knew definition, but I did not know how to explain it to someone else. In animation they showed the concepts with real life situation, and I was able to explain them to the next person.

LSD: Yes, for example, I didn't really understand how plants make their own food because since primary we have been told that plants manufacture their own food from the process of photosynthesis. But we didn't have a clear vision of how it really happens, but since we came here and saw those videos, we saw how it really happens, which organs and everything in the body is involved in gaseous exchange.

LSE: Yes, it has improved my Life Sciences Knowledge because I was able to process some terms very fast and easy.

LSF: It did improve my Life Sciences knowledge because now I am able to write concepts without struggling with the spellings since I saw them.

4. Discussion

The discussion is organised around the four components of scientific literacy used in the study: scientific knowledge, application, communication, and understanding of science in society. Improvements in conceptual understanding and application skills are supported by both test evidence and interview statements. The study investigated how learners' exposure to and use of e-modules and learning applications influence their scientific literacy in Grade 11 Life Sciences, as well as their attitudes and perceptions regarding these tools, focusing on motivation, enjoyment, and perceived usefulness. The findings, organised under relevant thematic areas, revealed compelling evidence that digital tools significantly enhance learners' acquisition of content knowledge, scientific skills, and engagement in science learning.

Theme 1: Increased acquisition of knowledge through e-modules

Theme 1 focuses on conceptual understanding of Life Sciences content facilitated by e-modules rather than on scientific literacy as a whole. While improved understanding of complex biological processes contributed to scientific literacy development, the theme primarily reflects knowledge acquisition through visual and interactive representations. Data from pre- and post-tests, classroom observations, and learner interviews clearly indicated that the integration of e-modules and digital learning platforms such as Binogi and Google Classroom led to a marked improvement in learners' scientific literacy. Learners demonstrated a stronger grasp of complex Life Sciences topics, such as population

ecology and gaseous exchange. These tools provided interactive multimedia content, animated videos, quizzes, and simulations that made abstract scientific concepts more comprehensible and engaging. Importantly, the use of English as the medium of instruction within these applications supported inclusive learning for learners from diverse linguistic backgrounds. Learners developed core scientific literacy skills, including observation, conceptual understanding, and the ability to construct and apply knowledge. This aligns with the constructivist and connectivist learning frameworks, which prioritise active knowledge construction and networked learning environments (Suhendi & Purwarno, 2018). Supporting studies by Prasetyo et al. (2021) and Balalle (2024) confirm the effectiveness of digital tools in improving scientific comprehension and performance.

Theme 2: Improved scientific communication and application of knowledge

Post-intervention test results showed that learners not only improved their content knowledge but also their ability to read, write, and communicate in the language of science. Learners effectively applied scientific reasoning and concepts in assessments, reflecting a transition from rote learning to meaningful engagement with scientific content. Binogi's use of visual storytelling and voice-explained content enhanced literacy and communication skills. Learners expressed increased confidence in engaging with scientific texts and assessments, supported by ongoing interactions and formative feedback facilitated through platforms like Google Classroom. These findings reflect the views of Abdurrahman (2022) and Egger (2023), who emphasise that dynamic, learner-centred learning environments promote not only academic achievement but also deeper scientific reasoning capabilities.

Theme 3: Enhanced curiosity, motivation, and engagement

Learners' attitudes and perceptions toward digital tools were overwhelmingly positive. Thematic analysis revealed that these tools sparked learners' curiosity, fostered inquiry skills, and deepened conceptual understanding. Learners described the lessons as more enjoyable and interactive, with many preferring the digital approach to traditional instruction. Classroom observations supported these sentiments, revealing high levels of attention, participation, and enthusiasm, even among previously disengaged students. Features such as gamified quizzes, real-time feedback, and relatable multimedia content created a more personalised and motivating learning experience (Filgona et al., 2020; Liu et al., 2024). These findings support constructivist principles, wherein learners actively build knowledge through meaningful interactions, inquiry-based learning, and intrinsic motivation (McLeod, 2019). Although increased engagement may partly reflect the novelty of using digital tools, interview data suggest that improvements in conceptual clarity and reasoning were linked to repeated exposure to animations, opportunities for self-paced learning, and instant feedback, rather than novelty alone.

The findings show a strong positive impact of e-modules and learning applications on learners' conceptual understanding, engagement, and critical thinking. Classroom observations revealed that interactive multimedia elements like simulations, videos, and quizzes helped learners grasp abstract scientific concepts more effectively than traditional methods. These tools also supported self-paced learning, allowing learners to revisit complex topics and deepen their understanding. Pre- and post-test results supported these observations quantitatively. Before the intervention, learners struggled with higher-order scientific thinking, such as analysis and application. After using the digital tools, they improved in explaining scientific concepts, designing experiments, interpreting data, and forming evidence-based arguments. Learners also became better at relating Life Sciences content to real-world situations through simulations and case-based learning, which aligns with research emphasising real-life application as key to scientific literacy (OECD, 2023; Adenle et al., 2023).

Additionally, learners demonstrated improved conceptual understanding and engagement with Life Sciences content, particularly through visualisation and self-paced learning opportunities. Evidence for these improvements was primarily reflected in assessment performance and learner explanations during interviews, rather than direct measurement of broader competencies such as collaboration or communication. Learners engaged with peers via digital platforms, enhancing collaborative learning and scientific reasoning. Semi-structured interviews confirmed that learners found e-modules more engaging and supportive compared to traditional textbooks, appreciating features like interactivity, real-time feedback, and flexible access, which boosted motivation and independent learning. Despite these benefits, challenges such as unequal access to devices and varying digital literacy levels were noted, highlighting equity concerns in digital learning implementation. Nonetheless, when combined with collaborative and constructivist teaching approaches, e-modules and learning apps have significant potential to transform Life Sciences education by improving academic outcomes and fostering scientific literacy skills necessary for informed societal participation. Additionally, the qualitative findings were strengthened by incorporating direct learner quotations, narrative descriptions of classroom interactions, and examples of divergent experiences. These provide deeper insight into learner engagement and highlight both positive and challenging aspects of the intervention. Lastly, learner motivation and engagement were inferred from observation indicators such as sustained attention, voluntary interaction with digital resources, and interview statements describing enjoyment and perceived usefulness. However, these indicators do not provide direct evidence of deeper learning, which remains partially constrained by learners' ongoing difficulties with scientific terminology and explanation.

5. Conclusions

Although situated in a South African context, the findings of this study have broader international relevance, particularly for education systems facing challenges related to scientific literacy, learner engagement, and equitable access to quality science instruction. The results demonstrate that curriculum-aligned digital learning tools, when pedagogically integrated, can support scientific literacy development in diverse, resource-variable contexts. This study contributes to global discussions on technology-enhanced science education by providing empirical evidence applicable to both developed and developing education systems. As such, this study explored how learners' exposure to e-modules and digital learning applications influence scientific literacy in the Grade 11 Life Sciences classroom. Findings reveal that such tools align closely with the South African curriculum's (CAPS) goals by promoting deeper conceptual understanding and encouraging active engagement with scientific content. E-modules enabled learners to move beyond memorisation toward inquiry-based learning, where they could engage in scientific reasoning, and connect abstract concepts like population ecology and genetics to real-world contexts. This shift supports the development of core scientific literacy competencies, such as understanding, application, and communication of scientific ideas as outlined in the National Curriculum (Department of Basic Education, 2011).

In addressing learners' attitudes and perceptions, the study found that e-modules and digital tools increased learners' motivation, enjoyment, and perceived usefulness of Life Sciences content. Interactive simulations and animations helped make complex concepts more accessible and engaging, leading to improved comprehension and retention. Learners also reported feeling more confident and curious about scientific topics, which enhanced their willingness to participate in class discussions and explore content beyond the classroom. These tools fostered a more learner-centred, exploratory environment that supports scientific thinking, creativity, and problem-solving, which are key attributes of scientific literacy.

The study concludes that traditional, fact-based teaching methods in South Africa fall short in promoting scientific literacy and must be reformed. It recommends broader integration of ICT tools and digital learning applications in Life Sciences education, supported by teacher training and equitable access to resources. By bridging the digital divide and embedding inquiry-based, technology-enhanced instruction into the curriculum, schools can provide all learners with opportunities to engage meaningfully with science. This approach not only addresses existing gaps in comprehension and engagement but also prepares learners to participate in a scientifically literate society capable of informed decision-making and lifelong learning.

Future research should extend beyond a single classroom to examine how e-modules and learning applications function across diverse South African contexts. Multi-site studies involving rural, township, and urban schools would provide insight into contextual variations in digital access and learner engagement. Longer-term interventions spanning an entire academic year are required to investigate sustained improvements in scientific literacy and their impact on final examinations. Additionally, quasi-experimental or cluster-randomised designs would allow for stronger causal claims about the effectiveness of digital tools. Future studies should also explore targeted interventions for scientific data literacy, given the persistent difficulty with graph interpretation observed in this study. Research on digital equity, including zero-rated platforms, data-free modes, and school-provided devices would address one of the most significant barriers identified. Finally, the multilingual affordances of tools like Binogi warrant focused investigation to understand how language-switching supports conceptual understanding in multilingual classrooms.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/educsci16030395/s1>.

Author Contributions: Conceptualization, M.I.T. and M.S.M.; methodology, M.I.T.; formal analysis, M.I.T.; investigation, M.I.T.; data curation, M.I.T.; writing—original draft preparation, M.I.T.; writing—review and editing, M.I.T., M.S.M. and M.F.M.; visualization, M.I.T. and MSM; supervision, M.S.M. and M.F.M.; project administration, M.I.T. and MSM. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted in accordance with the ethics clearance requirements and approved by the University of Limpopo, Turfloop Research Ethics Committee (project number: TREC/1546/2023:PG; date of approval: 26 September 2023).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this article are not readily available because they were collected from a project under research ethics approval that limits access to only those participating in this project. This was done to ensure the privacy, anonymity, and safety of participants.

Acknowledgments: The authors would like to thank the study participants for their participation in the study. Our sincere gratitude is extended to the principals, educators, and learners of schools surveyed for their steadfast assistance and collaboration throughout the research process.

Conflicts of Interest: The authors declare no conflicts of interest.

References

- Abdurrahman, A. (2022). Integrated science curriculum in the unpredictable world. In N. Rezaei (Ed.), *Integrated education and learning. Integrated science* (Vol. 13). Springer International Publishing. https://doi.org/10.1007/978-3-031-15963-3_11.
- Adenle, A. A., De Steur, H., Mwongera, C., Rola-Rubzen, F., de Barcellos, M. D., Vivanco, D. F., Timilsina, G. R., Possas, C., Alders, R., Chertow, M., Poons, S., & Scholes, B. (2023). Global UN 2030 agenda: How can science, technology and innovation accelerate the achievement of sustainable development goals for all? *PLOS Sustainability and Transformation*, 3(2), e0000100. <https://doi.org/10.1371/journal.pstr.0000085>.
- Afroz Alam, M. (2023). Connectivism learning theory and connectivist approach in teaching and learning: A review of literature. *Bhartiyam International Journal of Education & Research*, 12(2), 1–15.
- Arizen, A., & Suhartini, S. (2019). Developing mobile learning learner worksheet based on socio-scientific-issues to enhance high school learners' literacy skill. *JPBI (Jurnal Pendidikan Biologi Indonesia)*, 6(1), 15–24. <https://doi.org/10.22219/jpbi.v6i1.11196>.
- Balaban, I., Rienties, B., & Winne, P.H. (2023). Information communication technology (ICT) and education. *Applied Sciences*, 13, 12318. <https://doi.org/10.3390/app132212318>.
- Balalle, H. (2024). Exploring student engagement in technology-based education in relation to gamification, online/distance learning, and other factors: A systematic literature review. *Social Sciences & Humanities Open*, 9, 100870. <https://doi.org/10.1016/j.ssaho.2024.100870>.
- Bingham, A., & Witkowsky, P. (2022). Qualitative analysis: Deductive and inductive approaches. In C. Vanover, P. Mihas, & J. Saldaña (Eds.), *Analyzing and interpreting qualitative data: After the interview* (pp. 133–146). SAGE Publications.
- Braun, V., & Clarke, V. (2019). Reflecting on reflexive thematic analysis. *Qualitative Research in Sport, Exercise and Health*, 15, 589–597. <https://doi.org/10.1080/2159676X.2019.1628806>.
- Broderick, N. (2023). Exploring different visions of scientific literacy in Irish primary science education: Core issues and future directions. *Irish Educational Studies*, 44(1), 73–93. <https://doi.org/10.1080/03323315.2023.2230191>.
- Creswell, J. W., & Creswell, J. D. (2023). *Research design: Qualitative, quantitative, and mixed methods approaches* (4th ed.). Sage.
- Department of Basic Education (DBE). (2011). *Curriculum and assessment policy statement (CAPS): Life sciences grades 10–12*. DBE.
- Dini, S., Ikhsan, M., Pamungkas, A., & Kuswanto, H. (2024). Integrating language and science through digital platforms. *Education Sciences*, 14, 98. <https://doi.org/10.3390/educsci14010098>.
- Egger, A. E. (2023, April 21). *What is the process of teaching science*. Carleton College. Available online: <https://serc.carleton.edu/30459> (accessed on 30 August 2025).
- Filgona, J., Sakiyo, J., Gwany, D. & Okoronka, A. (2020). Motivation in learning. *Asian Journal of Education and Social Studies*, 10, 16–37. <https://doi.org/10.9734/AJESS/2020/v10i430273>.
- Galletta, A. (2013). *Mastering the semi-structured interview and beyond: From research design to analysis and publication*. NYU Press.
- Goldie, J. G. S., (2016). Connectivism: A learning theory for the digital age? *Medical Teacher*, 38(10), 1064–1069. <http://dx.doi.org/10.3109/0142159X.2016.1173661>
- Hein, G. E. (2007). *Constructivist learning theory*. Lesley College Press.
- Hussain, S., Tadesse, T., & Sajid, S. (2015). Norm-referenced and criterion-referenced test in EFL classroom. *International Journal of Humanities and Social Science Invention*, 4, 24.
- Hwang, G. J., Wang, S. Y., & Lai, C. L. (2021). Effects of a social regulation-based online learning framework on students' learning achievements and behaviors in mathematics. *Computers & Education*, 160, 104031. <https://doi.org/10.1016/j.compedu.2020.104031>.
- Jackson, C., Mohr-Schroeder, M. J., Bush, S. B., Mairorca, C., Roberts, T., Yost, C., & Fowler, A. (2021). Equity-oriented conceptual framework for K-12 STEM literacy. *International Journal of STEM Education*, 8, 38. <https://doi.org/10.1186/s40594-021-00294-z>.
- Johnson, R. B., & Onwuegbuzie, A. J. (2004). Mixed methods research: A research paradigm whose time has come. *Educational Research*, 49, 14–26. <https://doi.org/10.3102/0013189X033007014>
- Joshi, D. R., Khanal, J., Sharma Chapai, K. P., & Adhikari, K. P. (2025). The impact of digital resource utilization on student learning outcomes and self-efficacy across different economic contexts: A comparative analysis of PISA, 2022. *International Journal of Educational Research Open*, 8, 100443. <https://doi.org/10.1016/j.ijedro.2025.100443>.
- Kaldaras, L., Wang, K. D., Nardo, J. E., Price, A., Perkins, K., Wieman, C., & Salehi, S. (2024). Employing technology-enhanced feedback and scaffolding to support the development of deep science understanding using computer simulations. *International Journal of STEM Education*, 11, 30. <https://doi.org/10.1186/s40594-024-00490-7>.
- Khazanchi, D., Bernstein, R., Dilger, T., Groth, A., Mirski, P. J., Ploder, C., & Spieß, T. (2022). Strategies and best practices for effective elearning: Lessons from theory and experience. *Journal of Information Technology Case and Application Research*, 24(3), 153–165. <https://doi.org/10.1080/15228053.2022.2118992>.

- Kvale, S., & Brinkmann, S. (2015). *Interviews: Learning the craft of qualitative research interviewing*. Sage.
- Liu, S., Reynolds, B. L., Thomas, N., & Soyoo, A. (2024). The use of digital technologies to develop young children's language and literacy skills: A systematic review. *SAGE Open*, 14(1), 1–18. <https://doi.org/10.1177/21582440241230850>.
- Ma, Y. (2023). The effect of inquiry-based practices on scientific literacy: The mediating role of science attitudes. *International Journal of Science and Mathematics Education*, 21, 2045–2066. <https://doi.org/10.1007/s10763-022-10336-9>.
- Mahajan, M., & Singh, M. K. (2017). Importance and benefits of learning outcomes. *IOSR Journal of Humanities and Social Science*, 22(3), 65–67.
- Mayer, R. E. (2024). The past, present, and future of the cognitive theory of multimedia learning. *Educational Psychology Review*, 36, 8. <https://doi.org/10.1007/s10648-023-09842-1>.
- McLeod, S. (2019). *Constructivism as a theory for teaching and learning*. Simply Psychology. Available online: <https://www.simplypsychology.org/constructivism.html> (accessed on 30 August 2025).
- Mikić, V., Keković, G., Mangaroska, K., Ilić, M., Kopanja, L., & Vesin, B. (2025). Exploring learner engagement in e-learning environments: A predictive analytics perspective. *International Journal of Human-Computer Interaction*, 1–24. <https://doi.org/10.1080/10447318.2025.2535530>.
- OECD. (2023). *PISA 2022 results (Volume I): The state of learning and equity in education*. PISA, OECD Publishing. <https://doi.org/10.1787/53f23881-en>.
- Olivier, J., & Kruger, D. (2022). Science education in South Africa. In R. Huang (Ed.), *Science education in countries along the Belt & Road: Lecture notes in educational technology*. Springer. https://doi.org/10.1007/978-981-16-6955-2_12.
- Osborne, J., & Allchin, D. (2024). Science literacy in the twenty-first century: Informed trust and the competent outsider. *International Journal of Science Education*, 47(15–16), 2134–2155. <https://doi.org/10.1080/09500693.2024.2331980>.
- Palinkas, L. A., Horwitz, S. M., Green, C. A., Wisdom, J. P., Duan, N., & Hoagwood, K. (2015). Purposeful sampling for qualitative data collection and analysis in mixed method implementation research. *Administration and Policy in Mental Health and Mental Health Services Research*, 42(5), 533–544. <https://doi.org/10.1007/s10488-013-0528-y>.
- PISA. (2022). *Scientific literacy*. Organisation for Economic Co-operation and Development (OECD). Available online: <https://www.oecd.org/pisa/> (accessed on 30 August 2025).
- Prasetyo, D., Mariani, A., & Alimah, S. (2021). Improvement of students' science literacy skills using STEM-based e-modules. *Journal of Innovative Science Education*, 10(2), 216–221.
- Rahmat, A., Arip, M. A. S. M., & Sofyan, H. (2020). Integration of ICT in science learning: A meta-analysis. *International Journal of Instruction*, 13(2), 301–318.
- Reginald, G. (2023). Teaching and learning using virtual labs: Investigating the effects on learners' self-regulation. *Cogent Education*, 10(1), 33. <https://doi.org/10.1080/2331186X.2023.2172308>.
- Rudolph, J. L. (2023). Scientific literacy: Its real origin story and functional role in American education. *Journal of Research in Science Teaching*, 61(3), 519–532. <https://doi.org/10.1002/tea.21890>.
- Schwan, S., & Cress, U. (2020). *The psychology of digital learning*. Springer. <https://doi.org/10.1007/978-3-319-49077-9>.
- Simamora, A. B., Widodo, W., & Sanjaya, I. G. (2020). Innovative learning model: Improving the learners' scientific literacy of junior high school. *International Journal of Recent Educational Education*, 1(3), 271–285.
- Stevenson, N.A., VanLone, J., & Barber, B. R. (2020). A commentary on the misalignment of teacher education and the need for classroom behavior management skills. *Education and Treatment of Children*, 43, 393–404. <https://doi.org/10.1007/s43494-020-00031-1>.
- Suhendi, A., & Purwarno. (2018). Constructivist learning theory: The contribution to foreign language learning and teaching. In *The 1st annual international conference on language and literature, KNE social sciences & humanities, the 1st annual international conference on language and literature (AICLL) 2018 was held on April 18–19, 2018, at the Universitas Islam Sumatera Utara (UISU) in Medan, Indonesia* (pp. 87–95). KNE Open.
- Suwono, H., Latifatur, R. N., Saefi, M., & Fachrunnisa, R. (2021). Interactive socio-scientific inquiry for promoting scientific literacy, enhancing biological knowledge, and developing critical thinking. *Journal of Biological Education*, 57(5), 944–959. <https://doi.org/10.1080/00219266.2021.2006270>.
- Timotheou, S., Miliou, O., Dimitriadis, Y., Sobrino, S. V., Giannoutsou, N., Cachia, R., Monés, A. M., & Ioannou, A. (2023). Impacts of digital technologies on education and factors influencing schools' digital capacity and transformation: A literature review. *Education and Information Technologies*, 28(6), 6695–6726. <https://doi.org/10.1007/s10639-022-11431-8>.
- Valladares, L. (2021). Scientific literacy and social transformation: Critical perspectives about science participation and emancipation. *Science & Education*, 30(3), 557–587. <https://doi.org/10.1007/s11191-021-00205-2>.

- Wang, Y. (2022). A comparative study on the effectiveness of traditional and modern teaching methods. In *Proceedings of the 2022 5th international conference on humanities education and social sciences (ICHESS 2022)* (pp. 270–277). Atlantis Press SARL. https://doi.org/10.2991/978-2-494069-89-3_32.
- Wikanta, W., & Susilo, H. (2022). Higher order thinking skills achievement for biology education learners in case-based Biochemistry learning. *International Journal of Instruction*, 15(4), 835–854. <https://doi.org/10.29333/iji.2022.15445a>.
- Yin, R. K. (2024). *Case study research and applications* (7th ed.). Sage.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.