International Journal of Contemporary Sciences (IJCS)
Vol. 4, No. 7, 2026: 2009-2026

Transformation of Elementary Science Learning Through Technology-Enhanced Pedagogy to Foster Scientific Literacy

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A R T I C L E I N F O

Keywords: Elementary Science Education; Technology-Enhanced Pedagogy; Scientific Literacy; Digital Learning Media; Primary School

Received : 15 May
Revised : 20 June
Accepted: 30 July

A B S T R A C T

This study aims to analyze the transformation of technology-enhanced pedagogy in elementary science learning and its contribution to fostering scientific literacy, offering a contextual model of digital based inquiry rarely examined at the elementary level. Using a descriptive qualitative approach, data were collected over one academic semester through classroom observation, in depth interviews, and documentation involving science teachers, fourth and fifth grade students, and the school principal at a public elementary school in Makassar City. Findings show that integrating Google Classroom, PhET Simulations, Quizizz, Canva, and augmented reality shifted learning from memorization toward active inquiry, improving conceptual understanding, process skills, curiosity, and digital scientific literacy, despite infrastructure and supervision challenges, implying that well designed technology integration can effectively strengthen young learners' scientific literacy

DOI: https://doi.org/10.55927/8nw89866
E-ISSN: 3047-4078
https://journalijcs.my.id/index.php/ijcs

INTRODUCTION

The rapid development of digital technology in the twenty first century has significantly transformed the landscape of education at every level, including elementary education. Elementary science instruction, commonly known in the Indonesian curriculum as Ilmu Pengetahuan Alam (IPA) or as part of the integrated IPAS subject, plays a strategic role in cultivating children's early scientific literacy, curiosity, and rational thinking (Makkasau et al., 2022). As the foundation of citizens' ability to understand, evaluate, and apply scientific knowledge to everyday life, scientific literacy has become an essential competency emphasized in international assessments such as PISA and TIMSS, both of which have repeatedly highlighted the need for more contextual and technology-supported approaches to science instruction (Kong et al., 2022).

For decades, elementary science learning in many schools has been dominated by conventional methods such as lectures, rote memorization of definitions, and one way question and answer sessions. While effective for delivering basic factual knowledge, such approaches are often insufficient to nurture children's natural curiosity or to develop their scientific process skills of observing, questioning, experimenting, and interpreting evidence (Ceballos et al., 2026). Elementary age learners, who according to developmental theory are at the concrete operational stage of cognitive development, require learning experiences that are visual, hands on, and contextual in order to construct meaningful scientific understanding (Sahabuddin et al., 2023). Technology-enhanced pedagogy, through tools such as interactive simulations, augmented reality, and gamified assessment, offers a strategic pathway to bridge this developmental need with the abstract nature of many scientific concepts (Islami et al., 2025).

A public elementary school in Makassar City has begun implementing technology-enhanced pedagogy in its science instruction. Teachers utilize a combination of learning management systems, virtual simulation platforms, and visual design tools to deliver material, facilitate virtual experiments, and conduct formative assessment. This approach allows students to observe natural phenomena that are otherwise difficult to present directly in the classroom such as the water cycle, simple electrical circuits, or the structure of the solar system through vivid, interactive, and repeatable digital representations (Sukmawati et al., 2025). This shift illustrates a broader pedagogical transformation from rote transfer of scientific facts toward literacy based learning that demands active student engagement in constructing scientific understanding.

Scientific literacy itself is defined as the capacity to understand scientific concepts and processes, to apply them in evaluating real world phenomena, and to communicate scientific reasoning responsibly (A Framework for K-12 Science Education, 2012). In the context of elementary science education, scientific literacy is not measured merely by students' ability to recall facts, but by their capacity to relate scientific concepts to their immediate environment, to think critically about natural phenomena, and to develop a lifelong disposition of curiosity and evidence based reasoning (Sahabuddin et al., 2024). The use of digital media such as interactive simulations, visual infographics, and gamified

quizzes enables experiential learning, allowing abstract scientific concepts to become concrete and meaningful for young learners (Islami, 2025; Mayer & Fiorella, 2021). Prior research has shown that technology-enhanced learning environments significantly improve student engagement and learning outcomes in science education compared with conventional instruction (Acut & Antonio, 2023), while augmented reality media have been found effective in improving elementary students' understanding of complex topics such as the solar system (Islami et al., 2026).

Research on the transformation of elementary science learning through technology-enhanced pedagogy is important to identify forms of pedagogical innovation that are developmentally appropriate, engaging, and effective in cultivating young learners' scientific literacy. This study is expected to contribute to the development of contextual, student centered, and technology-integrated science teaching strategies, as well as to strengthen elementary schools' role in preparing a generation of scientifically literate, curious, and critically minded citizens who are ready to face the demands of the digital era.

LITERATURE REVIEW

Scientific literacy itself is defined as the capacity to understand scientific concepts and processes, to apply them in evaluating real world phenomena, and to communicate scientific reasoning responsibly (A Framework for K-12 Science Education, 2012). In the context of elementary science education, scientific literacy is not measured merely by students' ability to recall facts, but by their capacity to relate scientific concepts to their immediate environment, to think critically about natural phenomena, and to develop a lifelong disposition of curiosity and evidence based reasoning (Sahabuddin et al., 2024). The use of digital media such as interactive simulations, visual infographics, and gamified quizzes enables experiential learning, allowing abstract scientific concepts to become concrete and meaningful for young learners (Islami, 2025; Mayer & Fiorella, 2021). Prior research has shown that technology-enhanced learning environments significantly improve student engagement and learning outcomes in science education compared with conventional instruction (Acut & Antonio, 2023), while augmented reality media have been found effective in improving elementary students' understanding of complex topics such as the solar system (Islami et al., 2026).

METHODOLOGY

This study employed a descriptive qualitative approach, aiming to provide an in depth description of the transformation of technology-enhanced pedagogy in elementary science learning and its impact on fostering students' scientific literacy. This approach was chosen because it can reveal educational phenomena naturally, based on the direct experiences of teachers and students within the learning process (Ndihokubwayo et al., 2022). The population of this study consisted of all members of the school community involved in technology-enhanced science learning at a public elementary school in Makassar City, including the school principal, science teachers, and fourth and fifth grade students. Respondents were determined through purposive sampling, taking

into account their active involvement and intensity of participation in technology-enhanced science learning.

Data collection techniques included in depth interviews, participant observation, and documentation of both digital and face to face learning activities. Interviews were conducted to explore teachers' strategies for integrating digital media into science instruction, while observations focused on the implementation of classroom activities and student interaction during virtual experiments and digital assignments. The collected data were analyzed using the Miles and Huberman interactive analysis model, comprising three stages: data reduction, data presentation, and conclusion drawing/verification (Islami, 2025). Data validity was established through triangulation of sources and techniques, comparing the results of interviews, observations, and digital learning documents such as e-worksheets, simulation recordings, and student learning-outcome records (Islami et al., 2026). Through this method, the study is expected to provide a factual picture of how the transformation of technology-enhanced pedagogy is unfolding in elementary science classrooms, the factors that support and hinder it, and its implications for strengthening students' scientific literacy.

RESEARCH RESULT

The Transformation of Technology-Enhanced Pedagogy in Elementary Science Learning

The transformation of science learning at the elementary school under study is taking place in stages and in a planned manner. This transformation touches not only the learning-media aspect, but also encompasses changes in pedagogical strategy, learning-interaction patterns, and orientation toward strengthening students' scientific literacy relevant to developments in digital technology. In general, this transformation can be classified into three main aspects: (1) transformation of teacher learning strategies, (2) transformation of learning media and platforms, and (3) transformation of student learning activities.

1. Transformation of Teacher Learning Strategies

Science teachers at the school have experienced a shift from conventional, lecture-centered instruction toward digital learning that is participatory, exploratory, and contextual. Teachers are no longer the sole source of scientific knowledge, but act as facilitators guiding students' digital-based scientific inquiry.

Table 1. Changes in Elementary Science Teaching Strategies

No	Learning Aspect	Before Transformation	After Transformation
1	The Role of Teachers	Information center (teacher-centered)	Facilitator and guide of inquiry
2	Method	Lectures and memorization of definitions	Virtual experiments, project-based learning
3	Interaction	One-way	Two-way and collaborative

4	Evaluation	Written test	Digital quizzes, science projects, digital journals

This strategic transformation has increased student participation in learning and their ability to understand scientific concepts in a more contextual and applicable manner.

2. Transformation of Media and Learning Platforms

The most visible form of transformation is seen in the use of digital media and platforms in science learning. Teachers utilize various learning applications to deliver material, facilitate virtual experimentation, and strengthen students' conceptual understanding.

Table 2. Digital Media in Elementary Science Learning

No	Digital Media/Platform	Function in Learning
1	Google Classroom	Distribution of science materials and assignments
2	PhET Interactive Simulations	Virtual experiments (states of matter, simple circuits)
3	Quizizz	Interactive quizzes and formative assessment
4	Canva for Education	Science infographics on ecosystems and life cycles
5	Augmented Reality (AR) apps	3D visualization of the solar system and human body
6	YouTube Edu-Sains channels	Instructional videos of natural phenomena and experiments

The use of digital media helps students understand abstract scientific concepts more concretely through visualization, simulation, and interactive infographics.

3. Transformation of Student Learning Activities and Behavior

The transformation of technology-enhanced science pedagogy has also impacted student learning activities and behavior. Students have become more active, curious, and systematic in observing natural phenomena and documenting their findings.

Table 3. Changes in Student Learning Activities

No	Activity	Implementation Form
1	Virtual experiments	Simulating simple circuits and states of matter via PhET
2	Digital science journals	Recording observation results in a digital notebook or class blog
3	Collaborative projects	Group videos documenting local ecosystem observations
4	AR-based exploration	Exploring 3D models of the solar system and plant anatomy

This change shows that science learning is not only oriented toward mastering content, but also toward forming a curious, evidence-based, and environmentally aware disposition in students.

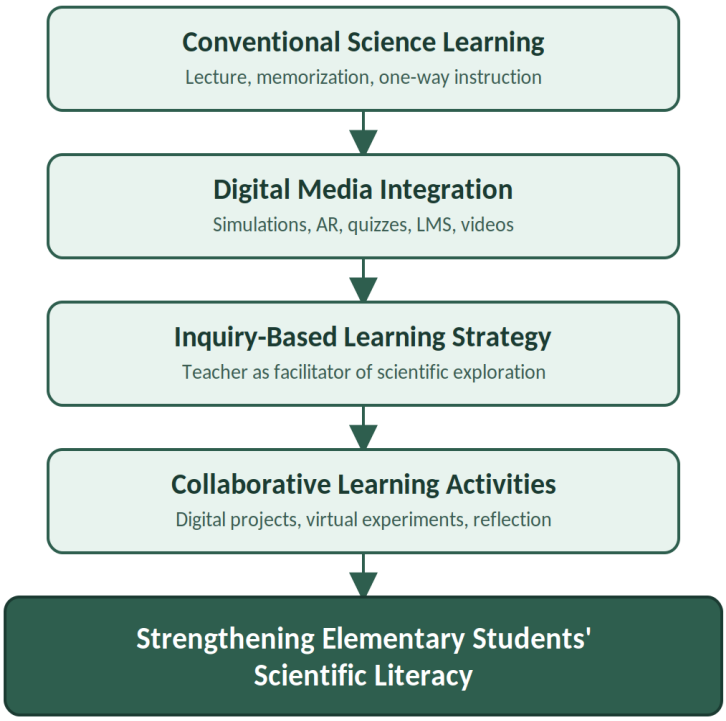

Figure 1. Transformation Scheme of Technology-Enhanced Elementary Science Learning

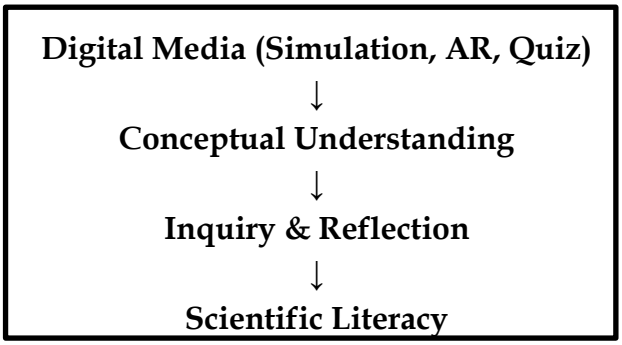

Figure 2. Relationship between Digital Media and Students' Scientific Literacy

The Impact of Technology-Enhanced Pedagogy on Improving Students' Scientific Literacy

The research results show that the implementation of technology-enhanced pedagogy has had a positive and significant impact on improving students' scientific literacy at the elementary school under study. This scientific literacy encompasses not only the ability to understand scientific concepts, but also the ability to conduct simple inquiry, interpret evidence, and apply scientific reasoning to everyday phenomena. In general, this impact can be seen in four main aspects: (1) conceptual understanding of science, (2) scientific process and inquiry skills, (3) scientific attitude and curiosity, and (4) digital-scientific literacy.

1. Improving Conceptual Understanding of Science

Technology-enhanced science learning facilitates students' understanding of abstract material through simulations, videos of natural phenomena, and scientific infographics. Students demonstrate a deeper understanding of scientific concepts and their application in everyday life.

Table 4. Impact of Technology-Enhanced Learning on Conceptual Understanding of Science

No	Scientific Literacy Indicator	Condition Before	Condition After
1	Understanding of natural phenomena	Abstract and memorization-based	Concrete, visualized, and contextual
2	Mastery of scientific vocabulary	Limited to textbook terms	Enriched through multimedia and digital references
3	Application of concepts	Passive, textbook-only	Applied to daily-life scientific phenomena

2. Improving Scientific Process and Inquiry Skills

Interviews and observations show that students are increasingly trained in scientific process skills through virtual experimentation and simple data interpretation. They are able to design basic experiments, record observations systematically, and interpret simple charts and graphs.

Table 5. Impact on Scientific Process and Inquiry Skills

No	Aspect	Research Findings
1	Observation	Students record digital observation data more systematically
2	Hypothesis and experimentation	Increased skill in designing simple virtual experiments
3	Data interpretation	Improved ability to analyze simple graphs from digital tools

3. Strengthening Scientific Attitude and Curiosity

The transformation of technology-enhanced pedagogy has also impacted students' attitudes and dispositions toward science. Learning is not only cognitively oriented, but also affective, so that scientific values such as curiosity, honesty, and environmental care are reflected in students' daily behavior.

Table 6. Impact on Students' Scientific Attitudes

No	Attitude Indicator	Changes That Occur
1	Curiosity	More proactive in asking questions and exploring phenomena
2	Care for environment	Greater ecological awareness following digital projects
3	Scientific honesty	More honest and accurate in reporting observation data

4. Improving Digital-Scientific Literacy

Technology-enhanced science learning encourages students to utilize digital tools positively to deepen their scientific understanding. Students are able to search for verified scientific sources and use digital media as a means of scientific exploration and reflection.

Table 7. Students' Digital-Scientific Literacy

No	Indicator	Forms of Behavior
1	Searching for verified scientific sources	Accessing trusted educational science websites and apps
2	Content production	Creating simple educational science videos and infographics
3	Digital scientific ethics	Careful in distinguishing verified information from science-related hoaxes

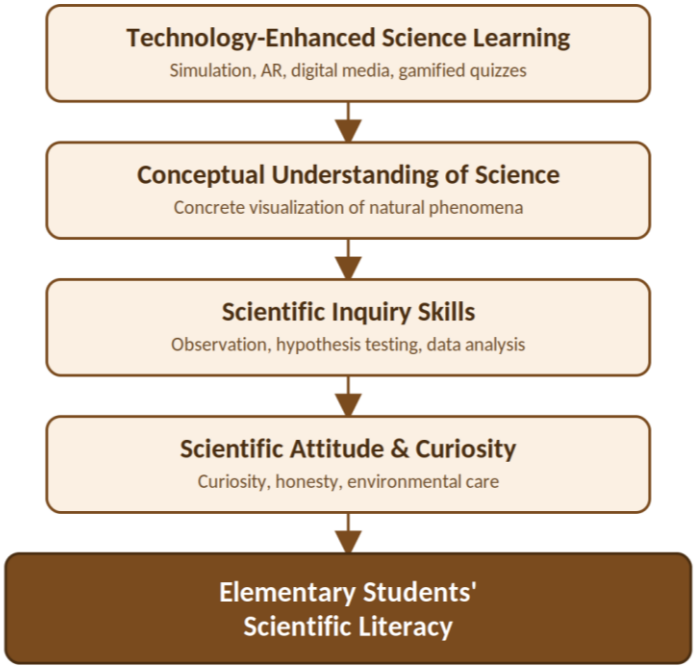

Figure 3. Model for Improving Elementary Students' Scientific Literacy through Technology-Enhanced Pedagogy

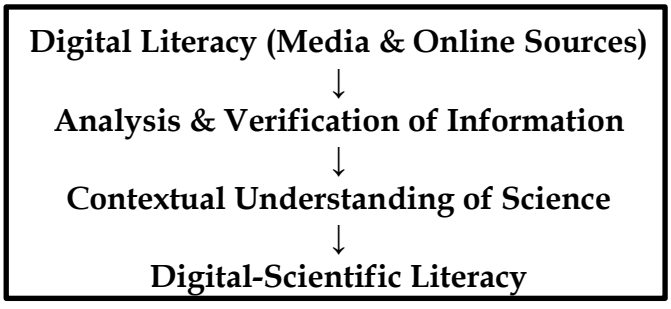

Figure 4. Relationship between Digital Literacy and Scientific Literacy

Challenges in Transforming Technology-Enhanced Elementary Science Learning

The research results show that although technology-enhanced pedagogy has had a positive impact on the process and outcomes of elementary science learning, its implementation still faces various challenges. These challenges are technical, pedagogical, developmental, and managerial in nature, affecting the effectiveness of optimal and sustainable implementation. In general, these challenges can be classified into four main aspects: (1) limited technological facilities and infrastructure, (2) digital competence of teachers and students, (3) learning and time management, and (4) challenges of age-appropriate content and digital supervision.

1. Limited Technology Facilities and Infrastructure

One of the main challenges identified was the limited support facilities for digital learning. Not all students have adequate digital devices and stable internet access, particularly those from families with limited economic resources.

Table 8. Challenges of Digital Facilities and Infrastructure

No	Challenge Form	Impact on Learning
1	Unstable internet access	Virtual experiments and online learning are disrupted
2	Limited device ownership	Student participation in digital activities is uneven
3	Limited school ICT/laboratory facilities	Hands-on and digital integration is not yet optimal

2. Digital Competence of Teachers and Students

The research also shows that not all teachers and students possess the same level of digital competence. Some teachers still require assistance in operating simulation and augmented-reality tools, while some students are not yet able to use technology optimally and independently.

Table 9. Challenges of Digital Competence

No	Subject	Challenge Form
1	Teacher	Limited mastery of simulation and AR-based learning tools
2	Student	Lack of independent focus during self-paced digital learning
3	Teacher & Student	Need to continuously adapt to new science-learning technologies

3. Learning and Time Management

The transformation of technology-enhanced science pedagogy demands more thorough time management and planning. Teachers require additional time to prepare digital experiments tailored to students' developmental level, while allocated learning time often does not accommodate the need for exploration and reflection.

Table 10. Challenges of Learning and Time Management

No	Aspect	Research Findings
1	Learning planning	Requires longer preparation time for digital experiment design
2	Implementation	Not all science topics are suitable for virtual simulation
3	Evaluation	Difficult to ensure authenticity of independent digital work

4. Challenges of Age-Appropriate Content and Digital Supervision

Technology-enhanced science learning at the elementary level also faces challenges in ensuring that digital content remains developmentally appropriate and safely supervised. Teachers need to curate digital media carefully to protect young learners from misleading or age-inappropriate content.

Table 11. Challenges of Age-Appropriate Content and Digital Supervision

No	Aspect	Problems
1	Age-appropriate content	Risk of exposure to unverified or overly complex science content
2	Screen-time balance	Difficulty balancing digital exploration with hands-on physical activity
3	Supervision	Limited parental and teacher monitoring during independent online exploration

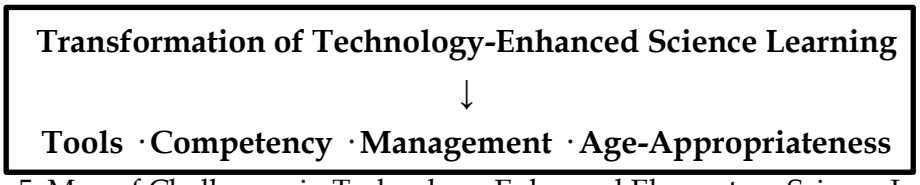

Figure 5. Map of Challenges in Technology-Enhanced Elementary Science Learning

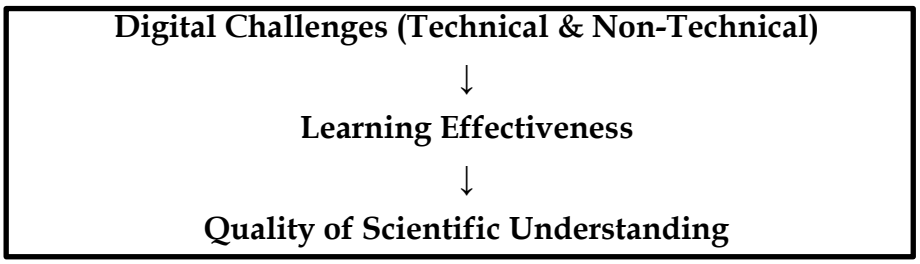

Figure 6. Relationship between Challenges and Effectiveness of Technology-Enhanced Science Learning

DISCUSSION

The Transformation of Technology-Enhanced Pedagogy in Elementary Science Learning

The transformation of science learning methods at the elementary school under study demonstrates a fundamental shift in early science education practices, occurring gradually, systematically, and in a planned manner. This transformation encompasses not only the use of technology as a learning medium but also a shift in pedagogical paradigms, teacher roles, learning-interaction dynamics, and the strengthening of students' scientific literacy relevant to the demands of digital era development. In this context, the

digitalization of science learning is not interpreted merely as a replacement of conventional methods, but as an effort to reconstruct the learning process to make it more contextual, exploratory, and developmentally meaningful for young learners.

The findings show that the transformation of science teaching strategies is characterized by a shift from a teacher centered approach to one oriented toward student inquiry. Before the transformation, science learning tended to be dominated by lectures and memorization of definitions, with the teacher as the primary source of knowledge. After the transformation, science teachers act as facilitators and guides, encouraging students to actively observe, simulate, and connect scientific concepts to real-world phenomena. This shift reinforces the view that effective technology integration requires a balanced mastery of technological, pedagogical, and content knowledge commonly framed as the TPACK model (Mishra & Koehler, 2006) so that digital tools genuinely support, rather than replace, sound pedagogical design.

This transformation in learning strategy has resulted in improved quality of learning interaction, shifting from one-way delivery to two way, collaborative exploration. Through virtual experiments and project based assignments, students become not only recipients of scientific information but also active participants in constructing scientific knowledge. Vygotsky's sociocultural theory emphasizes that social interaction and guided collaboration are crucial factors in children's cognitive development, particularly when mediated by tools that extend their zone of proximal development. In the elementary science classroom, digital simulations and collaborative digital projects function as such mediating tools, enabling students to explore phenomena that would otherwise be inaccessible in a physical classroom.

The transformation is also evident in changes to the learning evaluation system. Evaluation, which previously focused on written tests, has evolved into authentic assessment through digital quizzes, science projects, and digital reflective journals. (Wilson & Leslie, 2016) emphasize that authentic assessment is highly relevant in contemporary learning because it can measure cognitive, affective, and psychomotor dimensions of learning more holistically. In the context of elementary science, digital evaluation such as Quizizz based formative assessment has been found to have a positive influence on students' science learning outcomes, as it increases motivation while providing immediate, low-stakes feedback (Annisa & Erwin, 2021).

In addition to changes in teaching strategy, the transformation of science learning is also supported by diverse digital media and platforms. The use of learning management systems such as Google Classroom facilitates structured distribution of materials and assignments, while interactive simulation platforms such as PhET allow students to manipulate variables and observe cause-and-effect relationships safely and repeatedly. Meanwhile, the use of augmented reality applications for topics such as the solar system has been shown to improve elementary students' learning outcomes by making abstract astronomical concepts concrete and explorable (Annetta et al., 2024). Mayer's cognitive theory of multimedia learning explains that combining visual and verbal

representations enhances comprehension and retention more effectively than text alone, which is particularly relevant for elementary learners whose abstract reasoning is still developing (Mayer & Fiorella, 2021).

The use of gamified media such as Quizizz and design tools such as Canva for Education helps increase student motivation and enriches the variety of science instruction, serving not only as evaluation tools but also as a means of strengthening students' visual and digital literacy. Consistent with a systematic review of technology integrated pedagogical approaches, digitally mediated science instruction has been found effective in improving students' inquiry skills and fostering scientific literacy across various educational levels (Kong et al., 2022; Sidiq et al., 2025).

The transformation of technology enhanced pedagogy has also brought meaningful changes to student learning activities and behavior. Students have become more active and curious in observing natural phenomena and more systematic in documenting their findings. Collaborative digital projects such as group videos documenting local ecosystems strengthen social interaction and shared scientific reasoning among students, consistent with problem based and project-based learning research demonstrating gains in critical thinking skills through active, collaborative engagement (Ceballos et al., 2026). Furthermore, students' habit of recording observations in digital science journals demonstrates a strengthening of digital scientific literacy: students not only consume scientific information but also begin to responsibly produce simple scientific content. Gilster defines digital literacy as the ability to understand, evaluate, and critically use information within a digital environment (Gilster & Watson, 1997); in elementary science learning, this literacy is essential so that students can distinguish credible scientific sources from misleading information encountered online.

Overall, these findings indicate that the transformation of technology-enhanced pedagogy at the elementary school under study is an integrative process linking digital tool adoption with strengthened inquiry based strategies, collaborative learning activities, and the development of students' digital scientific literacy. This transformation confirms that science learning in the digital era is oriented not only toward mastery of content, but also toward the formation of curious, evidence based, and technologically adaptive young learners. The Science Technology Society approach, shown in meta analytic research to significantly improve science learning outcomes across educational levels including elementary school (Acut & Antonio, 2023), reinforces that digitally mediated, context-rich instruction can meaningfully strengthen the quality of elementary science education when it is pedagogically well designed.

Impact on Improving Students' Scientific Literacy

The research results show that technology-enhanced pedagogy has had a positive and significant impact on improving students' scientific literacy at the elementary school under study. In this study, scientific literacy is defined not only as the ability to understand scientific concepts textually, but also as the capacity to conduct simple scientific inquiry, interpret evidence, and relate

scientific knowledge to everyday phenomena. This finding reinforces the framework proposed by the National Research Council, which emphasizes that science education should be directed at practices, crosscutting concepts, and core disciplinary ideas that together build a coherent and applicable understanding of science from an early age.

The improvement in students' scientific literacy is clearly evident in their conceptual understanding of natural phenomena. Through the use of digital simulations, instructional videos, and scientific infographics, students are able to transform previously abstract concepts such as the water cycle or simple electrical circuits into concrete and applicable understanding. Understanding no longer stops at memorization but develops into an awareness of causal relationships between scientific phenomena and daily life. Multimedia learning theory explains that combining visual and verbal representation strengthens conceptual understanding because it engages both channels of cognitive processing simultaneously (Mayer, 2020); in elementary science instruction, this principle is particularly powerful for helping young learners visualize processes that cannot be directly observed.

Furthermore, technology-enhanced pedagogy has improved students' scientific process and inquiry skills. Observations and interviews show that students are increasingly trained to observe, record, and interpret data through structured virtual experiments. Reading proficiency and comprehension of scientific text have also been found to improve when mixed-reality and interactive digital tools are integrated into elementary science instruction, supporting deeper engagement with scientific concepts (Annetta et al., 2024). This demonstrates that technology-enhanced learning is not limited to improving factual recall, but extends to strengthening the procedural and epistemic dimensions of scientific literacy.

The impact of technology-enhanced pedagogy is also evident in strengthening students' scientific attitudes and curiosity. Science learning is not only cognitively oriented but also touches the affective dimension. Through interactive and reflective digital learning, students demonstrate increased curiosity, greater environmental awareness, and more honest reporting of observation results. Lickona's view that effective values education must integrate moral knowledge, moral feeling, and moral action in an interconnected manner (Kleinschmidt, 1994) is relevant here: the internalization of scientific values such as honesty and environmental care through digital learning encourages the formation of balanced cognitive and character development in young learners.

Finally, technology-enhanced pedagogy contributes significantly to improving students' digital scientific literacy. Students not only gain access to technology but also develop the ability to search for, select, and verify credible scientific sources. They are becoming accustomed to using trusted educational science websites and applications as references for understanding natural phenomena, and they are beginning to act as producers of simple scientific content through short videos and reflective science journals. Overall, these findings confirm that technology-enhanced pedagogy has direct implications for improving elementary students' scientific literacy holistically, encompassing

improved conceptual understanding, stronger inquiry skills, strengthened scientific attitudes, and balanced digital scientific literacy.

Challenges in Transforming Technology-Enhanced Elementary Science Learning

The research results show that although technology-enhanced pedagogy has had a positive impact on the quality of elementary science learning, its implementation still faces various complex challenges technical, pedagogical, developmental, and managerial in nature. This situation demonstrates that digital learning transformation is not simply a matter of technology adoption, but a systemic change that requires prepared human resources, adequate infrastructure, and a strong foundation of developmentally appropriate pedagogical design.

In terms of facilities and infrastructure, limited technological infrastructure remains a fundamental challenge. Not all students have adequate digital devices or stable internet access, a condition that results in uneven participation and has the potential to create a learning gap. This aligns with broader concerns raised in the digital divide literature, which highlights that unequal access to technology remains a major obstacle to equitable implementation of digital education, particularly in areas with limited network infrastructure.

In addition to limited resources, challenges also arise from the digital competence of teachers and students. This study found that digital literacy skills vary considerably; some teachers still require assistance in operating interactive simulation and augmented-reality tools, while some students are not yet fully able to use technology independently and responsibly. Effective technology-based learning depends heavily on the integration of pedagogical, content, and technological knowledge, as emphasized in the TPACK framework (Mishra & Koehler, 2006); without balanced mastery of these three domains, the use of technology risks becoming an additional burden rather than an effective instructional tool.

A further challenge relates to learning and time management. The transformation of technology-enhanced pedagogy requires more thorough planning, from the development of digital experiment materials to the implementation of evaluation. Teachers require additional time to design digital experiments tailored to students' developmental characteristics, while available instructional time often does not accommodate the need for exploration, reflection, and practice. (Darling-Hammond, 2006) emphasizes that meaningful learning requires sufficient time for exploration and reflection, which is often difficult to achieve if instructional time is not designed flexibly.

Equally important is the challenge of ensuring age appropriate content and adequate digital supervision. Technology-enhanced science learning opens a broad space for interaction with various sources of information online, but not all sources are curated or scientifically accurate for young learners. This research reveals teachers' concerns about the potential exposure of children to unverified or developmentally inappropriate content, as well as the difficulty of maintaining consistent supervision during independent digital exploration. From a

developmental perspective, this challenge requires teachers to act not only as instructors of scientific content but also as curators and guardians of age appropriate digital experiences, ensuring that students' independent exploration of science remains safe, accurate, and pedagogically productive.

Overall, the challenges of transforming technology-enhanced elementary science learning demonstrate that success is largely determined by infrastructure readiness, the digital competence of educators and students, adaptive learning-time management, and careful curation of age-appropriate digital content. These challenges are not unavoidable but can be managed through visionary school policy, ongoing teacher professional development, and the integration of digital and scientific literacy into the elementary curriculum. Thus, the transformation of technology-enhanced science pedagogy should be oriented not only toward efficiency and technological innovation, but also toward the sustainable development of children's scientific character and curiosity in the digital era.

CONCLUSIONS AND RECOMMENDATIONS

This study demonstrates that the transformation of technology-enhanced pedagogy in elementary science learning has led to meaningful changes in instructional practices and student learning experiences. The transformation occurred progressively, beginning with the integration of simple digital media and advancing toward inquiry-oriented, technology-supported learning environments that encourage active student engagement. Overall, the findings reveal improvements in three interconnected areas: teacher pedagogical practices, student learning behavior, and the enhancement of scientific literacy through the effective integration of digital technologies.

The findings show that science teachers have shifted from conventional teacher-centered instruction to more interactive and student-centered pedagogical approaches supported by digital technologies. Various platforms and applications, including Google Classroom, PhET Interactive Simulations, Quizizz, Canva for Education, and augmented reality tools, have been utilized to present scientific concepts in more engaging, contextual, and developmentally appropriate ways. Teachers reported that these technologies facilitated the explanation of abstract scientific concepts while increasing student participation, collaboration, and learning motivation throughout the instructional process.

The transformation has also positively influenced student learning behavior. Students have become more actively involved in observing scientific phenomena, conducting investigations, documenting findings, and evaluating information obtained from digital sources. Rather than relying solely on teacher explanations, students increasingly demonstrate the ability to explore digital simulations, analyze evidence, and connect scientific concepts with real-life situations. These findings indicate that technology-enhanced pedagogy contributes not only to the development of scientific literacy but also to the strengthening of digital literacy, critical thinking, and inquiry skills that are essential for learning in the digital era.

Despite these positive outcomes, several challenges remain, including limited technological infrastructure, disparities in teachers' digital competence, time constraints in implementing technology supported learning, and concerns

regarding the provision of safe and age appropriate digital content. Addressing these challenges is essential to ensure the sustainability and effectiveness of technology-enhanced pedagogy in elementary science education.

Based on these findings, several recommendations are proposed. Schools should strengthen digital infrastructure and ensure equitable access to educational technologies that support science learning. Continuous professional development programs should be provided to enhance teachers' technological, pedagogical, and content knowledge, enabling them to design meaningful inquiry-based science instruction integrated with digital tools. Educational policymakers are encouraged to formulate policies that support the sustainable implementation of technology-enhanced pedagogy while promoting safe, ethical, and developmentally appropriate technology use in elementary schools. Future research should investigate the long-term impact of technology-enhanced pedagogy on students' scientific literacy, critical thinking, and problem-solving skills across diverse educational settings using longitudinal or mixed-method research designs.

ADVANCED RESEARCH

This study has several limitations, including its focus on a limited number of elementary schools and the use of a qualitative approach, which may limit the generalizability of the findings. Future research is recommended to involve larger and more diverse samples, apply mixed-method or longitudinal designs, and examine the long-term impact of technology-enhanced pedagogy on students' scientific literacy, critical thinking, and learning outcomes.

ACKNOWLEDGMENT

The authors sincerely thank the participating schools, teachers, and all individuals who contributed to this research. The authors also appreciate the constructive suggestions provided by colleagues, which helped improve the quality of this manuscript.

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