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Digital-Based Deep Learning in Elementary Science Education: Implementation and Outcomes in Ecosystem Learning

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Article Info

Abstract

Deep learning, in the pedagogical sense—defined here as an instructional approach that engages students in exploration, discussion, and reflection to achieve meaningful conceptual understanding beyond surface memorization—has strong potential to transform elementary science education. This study describes the implementation of digital-based deep learning (D-DL) in Grade V science learning on the ecosystem topic at a public elementary school in Bekasi Regency, Indonesia. Using a qualitative descriptive approach, data were collected through observations, interviews (with the principal, teachers, and students), and documentation. Supporting quantitative data (pre-test/post-test scores and participation percentages) were analyzed descriptively (means and percentages). Digital media—simulation/experiment videos (concept exploration), interactive applications such as Wordwall (inquiry and formative feedback), and Google Classroom (collaborative reflection)—were used to facilitate the deep learning cycle. Participation rose from 35% to 81% and the mean test score from 63.2 to 83.7, with 86.4% of students achieving scores ≥70. Supporting factors included principal support and teacher readiness; constraining factors included limited devices, unequal digital skills, and connectivity issues. This study offers practical insights for implementing D-DL in elementary science aligned with Indonesia's Independent Curriculum

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INTRODUCTION

Science education at the elementary school level plays a crucial role in developing students' critical thinking and scientific reasoning skills (Eshuis et al., 2019). Through science learning, students are expected not only to understand facts about the natural world but also to develop

analytical thinking, observational skills, and the ability to draw conclusions from natural phenomena around them (Kibirige & Tsamago, 2019). Effective science instruction fosters curiosity and a scientific attitude that motivates students to continually explore and deepen their understanding (Farooq et al., 2024). Despite these important goals, science learning in many Indonesian elementary schools continues to face significant implementation challenges.

The most prevalent problem is the dominance of surface-level approaches in which students are taught to memorize facts or definitions without genuinely understanding the meaning or relationships between concepts (Pierce & Cleary, 2024; Ausubel, 1968). As a result, students' conceptual grasp remains shallow and less applicable to everyday life. For example, students may be able to state the definition of an ecosystem but struggle to explain how interactions between living organisms and their environment actually occur, or why those interactions are relevant to natural phenomena in their surroundings. The ultimate goal of science learning—connecting knowledge to real-world phenomena through deep and logical understanding—remains largely unmet (Farooq et al., 2024).

One primary reason for this superficiality is the limited range of methods and strategies employed by teachers (Timotheou et al., 2022). Many elementary school science lessons still rely on one-way lecture methods in which teachers deliver material verbally and students passively record information (Pierce & Cleary, 2024). In such settings, students have few opportunities to engage in higher-order thinking activities such as analysis, experimental design, or collaborative scientific discussion (Kibirige & Tsamago, 2019). Inquiry-based approaches such as discovery learning have shown potential in fostering conceptual understanding in elementary science, yet remain underutilized in many classrooms (Kibirige & Tsamago, 2019; Hmelo-Silver, 2004; Herrington & Oliver, 2000). The limited use of media and learning resources further constrains the creation of engaging and meaningful science learning experiences (Timotheou et al., 2022).

Deep learning, as a pedagogical concept, is operationally defined in this study as an instructional approach in which students actively engage in exploration, discussion, and structured reflection to construct meaningful understanding—as opposed to passive reception of information (Eshuis et al., 2019; Wen et al., 2020). In the classroom context of this study, deep learning was operationalized through three instructional behaviors: (1) teachers facilitating student-driven inquiry using digital media; (2) students engaging in collaborative small-group exploration; and (3) students completing structured reflection tasks following digital activities. This distinguishes the pedagogical concept of 'deep learning' from the computational meaning used in artificial intelligence and computer science (LeCun et al., 2015).

Internationally, deep learning approaches have been implemented in various educational systems. Finland adopts this approach by giving students freedom to explore topics of interest, integrating multiple disciplines, and emphasizing project-based problem-solving, with teachers acting as facilitators rather than information deliverers (Timotheou et al., 2022). Singapore integrates deep learning through its Teaching and Learning Innovations program, combining research-based learning and digital technology to increase student engagement and foster inquiry-based understanding (Eshuis et al., 2019). Canada employs project-based learning strategies connecting theory with real-life practice to develop analytical and reflective thinking (Eshuis et al., 2019; Krajcik & Shin, 2014). The

common lesson for Indonesia from these systems is the need to move beyond memorization-based evaluation toward assessment of critical thinking and problem-solving, supported by digital infrastructure and ongoing teacher professional development (Timotheou et al., 2022; Pellegrino & Hilton, 2012).

The deep learning approach is grounded theoretically in the SOLO Taxonomy (Wen et al., 2020), which emphasizes moving students from unistructural and multistructural levels of understanding toward relational and extended abstract levels—where they can connect concepts to real-world contexts. In digital learning environments, this progression is supported by technologies that provide interactive feedback, simulation, and opportunities for reflection (Wen et al., 2020; Timotheou et al., 2022). Students become active knowledge constructors rather than passive recipients, thinking critically, relating new knowledge to prior experience, and developing creative problem-solving skills (Bransford et al., 2000; Biggs & Tang, 2011). Research has shown that well-structured digital learning environments, when aligned with sound pedagogical principles, can significantly enhance conceptual understanding in science (Timotheou et al., 2022; Sung et al., 2016; Fullan & Langworthy, 2014).

Despite the potential of deep learning, its implementation in Indonesian elementary school classrooms remains limited. Many teachers do not fully understand how to design deep learning experiences, particularly in science subjects. Infrastructure limitations—especially regarding digital technology and supporting learning media—constitute major obstacles (Pierce & Cleary, 2024). Digital media in many elementary schools is underutilized despite its proven effectiveness in supporting interactive, contextual, and in-depth learning (Timotheou et al., 2022). This study focuses on the application of a digital-based deep learning approach in Grade V science learning at a public elementary school in Bekasi Regency—a context representing many Indonesian schools where potential exists for more interactive learning, but where device limitations and limited teacher experience with deep learning remain significant barriers. The study examines: (1) the extent to which D-DL implementation improves students' conceptual understanding of ecosystem science material; and (2) the supporting and inhibiting factors influencing this implementation.

METHOD

Research Design

This study employed a qualitative descriptive approach to provide a comprehensive account of the implementation of digital-based deep learning (D-DL) in an elementary science classroom. In addition to qualitative data (observations, interviews, and documentation), supporting quantitative data (pre-test and post-test scores and student participation percentages) were collected and analyzed using descriptive statistics (means and percentages) to triangulate and strengthen the qualitative findings. This mixed-format descriptive design—in which quantitative data serve as supporting evidence rather than as the primary analytical tool—is consistent with methodological frameworks for educational case studies (Creswell & Poth, 2018; Miles et al., 2014).

Research Setting and Participants

This research was conducted at a public elementary school in Bekasi Regency, West Java, Indonesia. The school was selected because it represents many Indonesian elementary schools: while potential exists to develop more interactive and inquiry-based learning, limitations in digital devices and teachers' familiarity with deep learning remain significant obstacles. Data collection took place over one month during the odd semester of the 2025/2026 academic year (October 2025), covering preparation, implementation, data collection, analysis, and validation.

Research participants comprised three groups: (1) Thirty-seven Grade V students, who served as the primary subjects for conceptual understanding measurement and whose perceptions of the D-DL approach were explored through interviews. (2) One fifth-grade science teacher who served as the primary facilitator responsible for designing and delivering D-DL instruction. (3) Eleven student-teachers (praktikan/field practice students from a teacher education program) who assisted with classroom management and small-group facilitation, along with the school principal, who provided contextual data on school policies and institutional support for digital learning.

Instruments and Data Collection

Data were collected using four complementary techniques. First, structured observation across six learning sessions was used to directly observe classroom processes, including digital media use and student-teacher interactions. The observation instrument covered seven activity indicators (Table 1) rated on a 1–4 scale. Second, semi-structured interviews were conducted with the principal, the fifth-grade teacher, student-teachers, and students to explore perceptions of D-DL implementation and identify challenges. Third, documentation—including lesson plans (RPP), digital media samples, and student work products—was collected as evidence of implementation quality. Fourth, a conceptual understanding test (pre-test and post-test) was administered to measure changes in students' understanding of ecosystem concepts, structured around eight cognitive sub-indicators at the C2 (comprehension) level of Bloom's revised taxonomy (Table 2), consistent with approaches to HOTS-based assessment in elementary science (Anderson & Krathwohl, 2001; Clark et al., 2016).

Table 1. Classroom Activity Observation Indicators

No.	Activity Indicator
1	Positive discipline implementation
2	Classroom orderliness
3	Interactive student activities
4	Constructive feedback from teacher
5	Adaptive instructional strategies
6	Clarity and quality of instructional delivery
7	Teacher attention and care for students

Table 2. Conceptual Understanding Test Indicators (Bloom's C2 Level)

No.	Conceptual Understanding Indicator
1	Explaining
2	Differentiating
3	Elaborating
4	Exemplifying
5	Expressing
6	Predicting
7	Transforming
8	Concluding

Table 3. Research Variables, Data Collection Methods, and Sources

Variables / Data	Data Collection Methods	Data Sources
Implementation of digital-based deep learning	Observation and Interviews	Fifth-grade teacher, student-teachers
Students' conceptual understanding of science	Tests (pre-test & post-test) and Interviews	Fifth-grade students (n=37)
Supporting and inhibiting factors	Interviews and Documentation	Principal, teacher, student-teachers

Data Analysis

Qualitative data from observations, interviews, and documentation were analyzed using the three-stage framework proposed by Miles et al. (2014): (1) data condensation—selecting, focusing, and transforming raw data; (2) data display—organizing condensed data into descriptive narratives, tables, and summary matrices; and (3) conclusion drawing and verification—generating interpretations and confirming them through triangulation. Credibility was established through source triangulation (cross-referencing data from teachers, students, and the principal) and technique triangulation (cross-referencing observations, interviews, and documentation), consistent with qualitative data analysis standards in health and education research (Miles et al., 2014). Quantitative data (pre-test, post-test, and participation scores) were processed using descriptive statistics (means and percentages) and N-gain scores without inferential testing, consistent with the study's descriptive character.

RESULTS AND DISCUSSION

Results

This study describes the implementation of a digital-based deep learning (D-DL) approach in Natural Science education for fifth grade students at elementary school. Data were collected through various techniques, including observation, interviews, documentation, and conceptual understanding tests (pre-test and post-test). The pre-test/post-test scores and participation percentages are presented

as supporting quantitative data and were analyzed descriptively (means and percentages) to complement the qualitative findings. The results of this data collection provide a clear picture of the implementation of the approach and its impact on students' conceptual understanding.

Interviews with the principal revealed that the implementation of a digital-based deep learning (D-DL) approach is part of the school's innovative efforts to improve the quality of learning, particularly in science subjects. The principal acknowledged the importance of using technology to support a more engaging and effective learning process. He stated that the use of digital media, such as instructional videos, interactive simulations, and online learning platforms like Google Classroom, provides a more engaging and meaningful learning experience for students. This opens up opportunities for students to be more involved in learning, not just receiving information from the teacher, but also exploring science concepts through technology. However, the principal also revealed several challenges still faced in implementing this approach. One major challenge is the limited availability of digital devices in schools. Devices such as computers, tablets, and projectors are insufficient to support all digital-based learning activities, resulting in only a small percentage of students being able to utilize them optimally. The principal also highlighted that despite teachers' willingness to implement digital-based deep learning, not all teachers possess the same level of skill in using technology in learning. Therefore, further training is needed so that teachers can optimize the use of technology for learning (Ally, 2019; Roblyer & Doering, 2013). In its implementation, digital ethics aspects are also important to instill from an early age so that students are able to use technology responsibly (Timotheou et al., 2022). These results align with the findings of Kibirige & Tsamago (2019)that a deep learning-based approach can significantly improve student learning outcomes

Interviews with fifth-grade teachers revealed similar views regarding the implementation of digital-based deep learning (D-DL). Teachers felt that this approach had a positive impact on students' engagement in science education. Prior to the implementation of this approach, most students simply memorized science concepts without truly understanding the relationships between concepts or their application in everyday life. Fifth-grade teachers stated that with the digital-based deep learning approach, students were more engaged in exploring concepts through engaging media, such as video simulations, interactive applications, and online quizzes. This made students more active in seeking understanding and connecting science concepts to the natural phenomena they encountered. However, Teachers also acknowledged that the implementation of digital-based deep learning does not always run smoothly. One challenge faced is the limited availability of digital devices. Although some devices are used, there are not enough for all students, so some students have to share devices. Furthermore, teachers also feel that some students struggle to use digital media due to differences in their technological abilities. Therefore, teachers need to adapt their learning methods and strategies, and pay more attention to students who need assistance accessing digital materials.

Interviews with students showed that the implementation of digital-based deep learning made them more interested in learning science. Seventy-eight percent of students reported enjoying science more after implementing this approach. They felt that the use of video experiments and online learning applications made difficult material easier to understand. For example, after watching a video about the food chain and interactions between living things, students felt they understood the concepts better and were able to connect them to events in the natural world around them.

Furthermore, students felt that digital-based learning provided opportunities for them to be more active in discussions and collaboration with their peers. Previously passive students became more confident in asking questions, offering opinions, and sharing their understanding of the topics being studied. However, some students still found digital-based learning challenging, primarily due to limited devices and other technical issues, such as unstable internet connections.

Observations were conducted over six learning sessions to observe the implementation of digital-based deep learning in science instruction. These observations provided a clear picture of the learning dynamics taking place in the classroom, as well as the extent to which students were engaged in the learning process.

Before implementing this approach, science education in fifth grade at SDN Tanjungbaru 02 tended to be dominated by teacher lectures and the use of Student Worksheets (LKS), which simply required students to memorize science concepts. Students tended to be passive and focused solely on test scores without truly understanding the relationships between concepts or their application. However, after implementing digital-based deep learning, the classroom atmosphere underwent significant changes. Students became more actively engaged in learning through various activities, such as watching simulation videos, discussing in small groups, and completing interactive assignments using learning applications like Wordwall and Google Classroom.
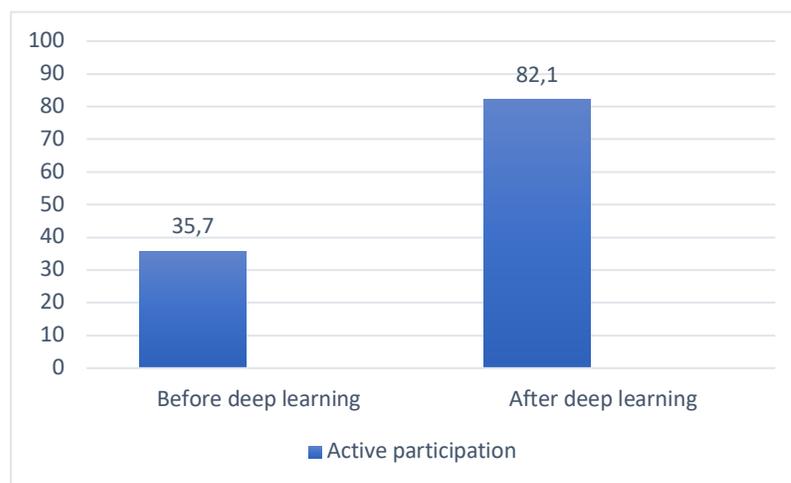

Figure 1. Increasing Active Participation Before and After Digital Based Deep Learning

Table 4. Classroom Activity Observation Result

No	Indicator	Pre-test (Scale 1-4)	Post-test (Scale 1-4)
1	Positive discipline implementation	1.5	3.5
2	Classroom orderliness	2.0	3.5
3	Interactive student activities	1.0	3.0
4	Constructive feedback from teacher	1.0	3.0
5	Adaptive instructional strategies	1.5	3.5
6	Clarity and quality of instructional delivery	1.5	3.0
7	Teacher attention and care for students	1.5	3.5

The observations indicate that students' active participation increased. Before implementing this approach, only about 35% of students actively participated in learning. After implementing digital-based deep learning, the student participation rate increased to 81%. This demonstrates that digital-based learning, which combines technology and collaboration, can increase student engagement in the teaching and learning process. Students become not only recipients of information but also active learners engaged in exploration and reflection on the science concepts they are learning.

Despite significant increases in student participation, some challenges remain. Limited digital devices mean some students have to share devices with their peers, which can reduce the effectiveness of technology use in learning. Furthermore, variations in technological abilities among students also affect their engagement levels. Some students with better technological skills can adapt more easily to digital media, while others with less skilled skills struggle to access learning materials or participate in activities involving technology.
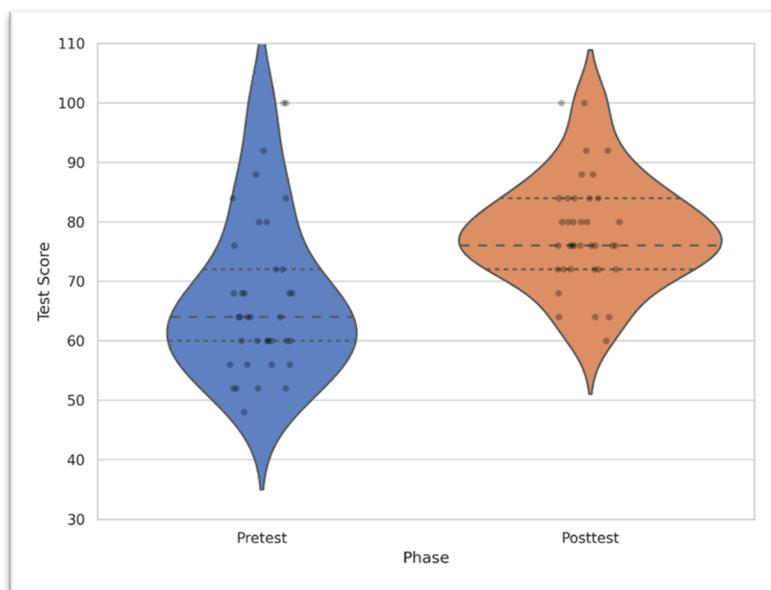

Figure 2. Distribution of Students' Pretest and Posttest Scores

Table 5. Conceptual Understanding Test Result

Indicator	Pre test	Post test	Ngain
Explaining	84	92	0,50
Differentiating	78,4	86,4	0,37
Elaborating	73,6	81,2	0,29
Exemplifying	72,8	81,2	0,31
Expressing	64,56	81,2	0,47
Predicting	43,04	78,64	0,63
Transforming	43,04	78,88	0,63
Concluding	37,68	50,08	0,20

Conceptual understanding tests were conducted before and after the implementation of a digital-based deep learning (D-DL) approach to measure students' improvement in science material, particularly regarding the concept of ecosystems and the relationships between living things. The pre-test showed that most students did not yet have a deep understanding of these concepts. Of the 37 students tested, only 11 (29.7%) scored above 70. Most students were only able to memorize terms in ecosystems without truly understanding the relationships between biotic and abiotic components. However, after the implementation of digital-based deep learning, the post-test results showed a significant improvement. A total of 32 students (86.4%) scored above 70, with the class average score increasing from 63.2 in the pre-test to 83.7 in the post-test. This improvement indicates that the implementation of a digital-based deep learning (D-DL) approach is effective in improving students' conceptual understanding, particularly in the material on ecosystems, food chains, and interactions between living things.

Analysis of the test results also showed that students who were previously only able to memorize concept definitions, after implementing digital-based deep learning, were able to better explain the relationships between concepts. For example, they were able to explain how the interactions between producers, consumers, and decomposers in an ecosystem can affect the survival of other living things. Furthermore, students were also able to provide real life examples from their own lives related to the science concepts they were learning, such as the relationships between plants, animals, and their surroundings.

Discussion

The substantial increase in student active participation—from 35% to 81% following the implementation of digital-based deep learning—reflects a fundamental shift in the nature of classroom engagement, from passive information reception toward active, student-driven inquiry. This shift is consistent with Wen et al.'s (2020) simulation-guided inquiry framework of Multimedia Learning, which posits that well-designed multimedia environments reduce extraneous cognitive load and free working memory for active processing. When students interact with ecosystem simulation videos and Wordwall quizzes, they are not merely consuming information; they are building internal representations through selection, organization, and integration of multimodal inputs. The observation data—where the most pronounced gains appeared in 'interactive activities' (1.0 to 3.0) and 'constructive feedback' (1.0 to 3.0)—indicate that the inquiry and feedback stages of the D-DL cycle were the primary drivers of this engagement shift. This aligns with Timotheou et al.'s (2022) framework, which identifies structured, technology-mediated student–environment interaction as the key mechanism through which digital tools improve learning outcomes.

The N-gain score pattern across the eight conceptual understanding sub-indicators reveals a theoretically coherent picture of how digital deep learning affects cognition. The highest N-gain values were recorded for 'predicting' (0.63) and 'transforming' (0.63), both sub-indicators that require applying understanding to novel or hypothetical scenarios. This finding supports the role of simulation-based activities—particularly ecosystem interaction videos—in fostering scenario-based conceptual application, consistent with research by Hung et al. (2022) on digital storytelling and conceptual transfer in elementary science. By contrast, the lowest N-gain was observed for

'concluding' (0.20), a sub-indicator requiring students to synthesize information into generalized statements. This suggests that while the D-DL cycle effectively develops comprehension and application, it provides insufficient scaffolding for the synthesis operations associated with extended abstract thinking in the SOLO Taxonomy (Wen et al., 2020). Future implementations should incorporate structured synthesis tasks—such as guided concept mapping or collaborative essay writing—to strengthen this dimension.

A key finding of this study is that the effectiveness of the D-DL approach cannot be attributed to digital technology per se, but to the pedagogical architecture within which each tool was embedded. Simulation and experiment videos functioned as 'concept exploration' triggers—presenting phenomena (e.g., food chain disruption, predator-prey dynamics) that activated prior knowledge and generated productive uncertainty, consistent with Eshuis et al.'s (2019) argument that deep learning begins with authentic inquiry rather than information delivery. Interactive applications (Wordwall) provided immediate formative feedback loops that prompted self-monitoring and error correction—a function analogous to the 'adaptive teaching' component of Timotheou et al.'s (2022) framework. Google Classroom submissions, meanwhile, created structured opportunities for written reflection, enabling students to consolidate understanding through verbalization—a process supported by constructivist learning theory (Mayer, 2009; Vygotsky, 1978). The sequential logic of explore–inquire–reflect thus operationalized deep learning not as a single instructional event but as a cyclical process unfolding across sessions, which explains the cumulative pattern of improvement observed across the six-session intervention.

The emergence of digital ethics as a relevant pedagogical dimension in this study warrants explicit attention in the discussion. As the school principal noted, the expanded use of technology in the classroom created new responsibilities: students needed guidance on responsible use of digital platforms, appropriate online communication, and critical evaluation of digital content. This concern aligns with Clark et al.'s (2016) framework of digital literacies, which argues that effective technology integration in education requires not only technical competence but also critical and ethical digital citizenship (Beetham & Sharpe, 2013; Dede, 2010). Timotheou et al. (2022) similarly identify digital citizenship education must be embedded from the elementary level to ensure that students develop as responsible technology users. The incorporation of brief digital ethics discussions within the D-DL sessions—as reported by the classroom teacher—represents a promising practice that future implementations should formalize into a structured component of the instructional design.

Three enabling factors consistently emerged from interview and observation data as foundational to the implementation's success. First, principal-level policy endorsement created institutional legitimacy for technology use, removing bureaucratic barriers and signaling to teachers and students that digital learning was a school priority—a dynamic consistent with findings by Timotheou et al. (2022) on the enabling role of institutional support in technology-enhanced learning. Second, the classroom teacher's proactive instructional design—translating the deep learning framework into concrete session plans with clearly differentiated digital media roles—was the proximate driver of student learning. Research on teacher digital competency consistently identifies teacher agency and design thinking, rather than technology availability alone, as the primary mediator of educational outcomes (Timotheou et al., 2022; Romero-García et al., 2022; Mishra & Koehler,

2006; Chai et al., 2010). Third, students' intrinsic motivation and enthusiasm—evidenced by 78% reporting increased enjoyment of science—created the affective conditions under which deeper cognitive engagement became possible. Sung et al. (2016), in a meta-analysis of mobile device integration across 110 studies, similarly found that motivational enhancement was both a prerequisite and a product of well-designed digital learning environments.

The inhibiting factors identified in this study—device scarcity, unequal digital competencies among students, and unstable internet connectivity—are not isolated to SDN Tanjungbaru 02 but represent structural constraints characteristic of many Indonesian elementary schools, particularly those outside major urban centers (Timotheou et al., 2022; Pierce & Cleary, 2024). Device scarcity required students to share equipment, reducing individual engagement time and creating dependence on cooperative rather than independent exploration—a constraint that partially explains the lower N-gain in 'concluding', which requires independent synthesis (Johnson & Johnson, 2009). Variation in students' prior digital experience introduced differential access to learning, disadvantaging students with less prior technology exposure and risking a widening of existing learning gaps. These constraints are consistent with the 'digital divide' literature, which cautions that technology integration without accompanying equity interventions can reproduce rather than reduce educational inequality (Timotheou et al., 2022; Pierce & Cleary, 2024; UNESCO, 2015). Mitigation strategies employed in this study—device-sharing groups, differentiated teacher support, offline backup materials—were partially effective, but point to the need for systematic institutional investment in ICT infrastructure and targeted digital skills development for students with limited technology backgrounds (Pane et al., 2015).

Taken together, the findings of this study are consistent with the growing body of international evidence demonstrating that technology-mediated deep learning approaches can significantly improve both engagement and conceptual understanding in elementary science education (Sung et al., 2016; Hung et al., 2022; Timotheou et al., 2022; Wen et al., 2020). However, this study makes a distinctive contextual contribution by demonstrating that these outcomes are achievable within the resource constraints typical of Indonesian public elementary schools—where device-to-student ratios are low, teacher technology proficiency varies widely, and connectivity is unreliable. The fact that meaningful learning gains were achieved despite these constraints underscores the primacy of pedagogical design over technological infrastructure. This aligns with Eshuis et al.'s (2019) analysis of the Merdeka Belajar framework, which argues that deep learning in the Indonesian context requires first a shift in instructional paradigm—from transmission to inquiry—before technology can serve as an effective enabler. The study thus affirms that digital tools, when deployed within a coherent explore–inquire–reflect architecture, can function as effective mediators of deep learning even in under-resourced settings, provided that teacher design capability and institutional support are present.

CONCLUSION

This study demonstrates that a structured, digital-based deep learning (D-DL) approach can meaningfully improve both the process and outcomes of Grade V science learning on the ecosystem topic in an Indonesian elementary school context. Specifically, student active participation increased

from 35% to 81% and the class mean conceptual understanding score rose from 63.2 to 83.7, with 86.4% of students achieving mastery (score ≥ 70). These improvements are attributable to a shift in instructional design from lecture-and-memorization-dominated delivery toward a structured cycle of digital exploration (simulation/experiment videos), guided inquiry (interactive applications), and collaborative reflection (online platforms).

The central finding is that digital technology, when integrated within a coherent pedagogical framework rather than used as a supplementary presentation tool, serves as an effective mediator of deep learning. Students not only demonstrated higher test scores but showed qualitatively deeper conceptual engagement: they could explain ecosystem interactions, predict consequences of disruption, and connect scientific concepts to real-world observations—markers of the relational understanding level in SOLO Taxonomy. The highest N-gain sub-indicators (predicting and transforming, both 0.63) confirm that simulation-based activities particularly enhanced higher-order conceptual application, while the lower N-gain for 'concluding' (0.20) signals that synthesis skills require more structured scaffolding in future implementations.

From an implementation perspective, success was shaped by two clear categories of factors. Enabling factors included principal support, teacher readiness, and students' enthusiasm for interactive digital activities. Inhibiting factors included limited device availability, variation in students' digital competencies, and unstable internet connectivity. Addressing these inhibiting factors—through ICT investment, structured teacher professional development in deep learning design, and digital citizenship education embedded within subject learning—is essential for sustainable and equitable implementation.

This study has limitations that should inform future research. The qualitative descriptive design and single-school context limit generalizability; quantitative data served a supporting rather than inferential role. Future research should employ quasi-experimental designs across multiple schools, explore variation across content areas and grade levels, and include complementary qualitative indicators (student reasoning logs, digital discussion transcripts, structured reflection analyses) to provide richer evidence of deep learning processes beyond test score gains. Longitudinal tracking of conceptual retention would further strengthen the evidence base for digital-based deep learning in Indonesian elementary education.

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