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DEVELOPMENT OF A DIGITAL-BASED PJBL MODEL TO ENHANCE STUDENTS' SCIENTIFIC LITERACY SKILLS DURING A PERIOD OF DISRUPTION

Rosyidah Lian Najah*[1] , Nur Indah Setyowati[2]
[1,2] *Universitas Islam Darul 'Ulum Lamongan*

* Corresponding Author: *rosyidah.2024@mhs.unisda.ac.id*

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ABSTRACT

The low level of scientific literacy among Indonesian students, as reflected in the 2022 PISA results, highlights the need for an innovative science learning approach that is relevant to the learning context. This study aims to develop a Project-Based Learning (PjBL) model integrated with digital technology and to evaluate its validity, practicality, and effectiveness in enhancing the scientific literacy of fourth-grade students at an Islamic elementary school (*madrasah ibtidaiyah*) regarding the topic of environmental pollution. The novelty of this research lies in the systematic integration of digital technology into every stage of the PjBL syntax, whereby technology supports assessment, collaboration, project monitoring, presentations, and reflection throughout the learning process. The study employs a Research and Development (R&D) approach using the ADDIE model. A limited-scale trial was conducted with 25 fourth-grade students at MI Islamiyah Sumurgenuk, utilizing a one-group pretest-posttest design. The results indicate that the developed model possesses a very high level of validity, as assessed by subject matter experts (89%) and media experts (91.5%). The model also demonstrates a high level of practicality, evidenced by student responses (88.8%) and the successful implementation of the learning syntax (91.7%). The effectiveness of the model is shown by an N-gain score of 0.616 falling into the moderate category and a statistically significant improvement in students' scientific literacy scores between the pretest and posttest ($p < 0.001$). The developed model provides a structured, technology-assisted PjBL framework that facilitates active, contextual, and collaborative science learning. This model serves as an innovative alternative for strengthening students' scientific literacy, particularly in the study of environmental pollution within primary education, supported by digital technology.

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INTRODUCTION

The rapid development of digital technology has fundamentally transformed educational practices and created new opportunities for more interactive and meaningful science learning. However, one of the persistent challenges in Indonesian education is the low level of students' scientific literacy. According to the PISA 2022 results, Indonesian students obtained a science literacy score of 383, substantially below the OECD average of 485 (Dian dkk., 2022). This condition indicates that science learning in Indonesia still faces difficulties in developing students' scientific reasoning (OECD, 2023), particularly their ability to explain scientific phenomena, design scientific investigations, and interpret evidence and data. Therefore, science learning needs to move beyond knowledge transmission toward learning experiences that actively engage students in investigating and solving authentic problems.

One of the factors contributing to low scientific literacy is the continued dominance of conventional, teacher-centered learning and limited student involvement in investigative activities (Fadlurrahman et al., 2026). Learning that emphasizes memorization and theoretical knowledge may limit students' opportunities to connect scientific concepts with phenomena in their everyday environment. Ideally, science learning should be active, contextual, and meaningful (Sharma, 2017). Project Based Learning (PjBL) offers an appropriate approach because it engages students in authentic projects that require investigation, collaboration, problem solving, and the application of scientific concepts. Previous research has demonstrated that PjBL can improve students' conceptual understanding and science process skills (Yuniasih et al., 2022), indicating its potential to support the development of scientific literacy.

Nevertheless, the effectiveness of PjBL depends on how its learning stages are implemented. In practice, PjBL still faces challenges, including limited instructional time, inadequate learning resources, and insufficient integration of digital technology (Anggraini, 2025). These limitations may make it difficult for teachers to facilitate the entire PjBL process systematically and provide continuous guidance and feedback to students. Although digital technology provides opportunities to overcome these limitations through online platforms, interactive media, and other digital learning resources (Silvester et al., 2024), its use in PjBL is often not integrated systematically across the entire learning process.

Thus, the existing implementation of PjBL leaves a gap between the potential of digital technology and its systematic use to support each stage of project-based science learning.

This gap indicates the need for a digital-integrated PjBL model in which technology is not merely used as an additional presentation medium but is embedded throughout the learning syntax to support students' scientific literacy. In this study, digital technology is systematically integrated into all six stages of PjBL: determining fundamental questions, planning the project, arranging the schedule, monitoring project progress, assessing project outcomes, and evaluating the learning experience. The integration includes digital tools for initial assessment and problem identification, collaborative project planning, digital scheduling and project documentation, teacher monitoring and feedback, presentation and peer evaluation, and student reflection. This design distinguishes the proposed model from conventional PjBL implementations in which digital technology may be used only at particular stages or as supplementary media. The novelty of this study therefore lies in the development of a structured digital-integrated PjBL model that connects the complete PjBL syntax with digital tools while explicitly aligning each stage with scientific literacy competencies. The model is designed not only to facilitate project completion but also to provide continuous opportunities for students to explain scientific phenomena, design investigations, evaluate information and evidence, and communicate scientific findings.

The proposed model also addresses a practical need in madrasah ibtidaiyah (MI) science education by combining contextual environmental pollution projects with accessible digital learning tools. Environmental pollution was selected because it is closely related to students' everyday experiences and provides authentic contexts for observing phenomena, collecting information and evidence, interpreting data, and proposing solutions. The integration of digital technology within this contextual project is expected to strengthen students' engagement while providing teachers with a more systematic framework for implementing PjBL and monitoring students' learning processes. In this respect, the study contributes practically by providing an integrated learning model and supporting learning components that can guide teachers in implementing digitally supported project-based science learning.

Based on this research gap and the proposed novelty, this study aims to develop a digital-integrated Project Based Learning (PjBL) model for science learning in MI and to determine its validity, practicality, and effectiveness in improving students' scientific literacy on the topic of environmental pollution. Specifically, the study examines whether the developed model is feasible according to expert assessment, practical for classroom implementation, and effective in improving students' scientific literacy. Through this

development, the study is expected to provide a systematic model for integrating digital technology into PjBL and contribute to the development of more contextual, interactive, and scientifically oriented science learning in the digital era.

RESEARCH METHODOLOGY

Research Design and Development Procedure

This study employed a Research and Development (R&D) design aimed at developing a digital-integrated Project-Based Learning (PjBL) model and examining its validity, practicality, and effectiveness in improving students' scientific literacy. The development procedure adopted the ADDIE model, consisting of five systematic phases: Analysis, Design, Development, Implementation, and Evaluation (Sugiyono et al., 2019). ADDIE was selected because of its structured yet flexible procedure, which allows the development process to be conducted systematically through needs identification, product design, development and validation, field implementation, and evaluation. The model has also been widely applied in the development of learning devices (Hidayat et al., 2021) and is considered suitable for integrating digital technology into instructional design (Lojan-Carrion et al., 2025).

Analysis Phase

The Analysis phase consisted of a literature review and a needs analysis. The literature review examined theoretical and empirical studies related to the PjBL model, scientific literacy, the integration of digital technology in science learning, and relevant previous research.

The needs analysis was conducted through two methods: (1) direct observation of science learning activities in three public Madrasah Ibtidaiyah Islamiyah Sumurgenuk, and (2) semi-structured interviews with five science teachers. Observations focused on instructional strategies, student engagement, and the availability and use of digital technology in the classroom. Interviews explored teachers' perceptions of project-based learning, challenges in implementing PjBL, and their experience with digital tools.

The key findings from the needs analysis included:

- Teachers predominantly used lecture-based methods with limited student-centered activities
- Students showed low engagement and difficulty in connecting scientific concepts with real-world phenomena.
- Digital technology was available but used only for presentation purposes, not integrated into the learning process.

- Teachers expressed interest in PjBL but lacked structured guidance and digital resources to implement it effectively.

These findings served as the basis for determining the product specifications: a structured PjBL model with systematic digital integration at every syntax stage, supported by comprehensive learning devices and digital platforms.

Design Phase

The Design phase focused on developing the initial framework and components of the digital-integrated PjBL model based on the findings of the Analysis phase. The product consisted of four main components:

1. Learning Model Syntax: Six PjBL stages (determining fundamental questions, project design planning, schedule arrangement, monitoring, outcome assessment, and experience evaluation) integrated with digital platforms at each stage.
2. Learning Devices: Lesson plans (RPP), digital-based student worksheets (LKPD), and teaching materials.
3. Scientific Literacy Assessment Instrument: Reasoned objective test items developed based on PISA 2022 scientific literacy indicators.
4. Supporting Instructional Media: Tutorial videos explaining the use of digital platforms and project examples.

The learning activities and assessment components were designed with reference to the PISA 2022 scientific literacy indicators to ensure alignment between the learning model, learning activities, and intended scientific literacy outcomes (Ayu et al., 2025).

Development Phase

In the Development phase, all components of the digital-integrated PjBL model were developed according to the design specifications and subsequently subjected to expert validation.

Expert Validation of the Model

Product validation involved two experts: (1) a science learning material expert with over 10 years of experience in primary science education, and (2) a media/educational technology expert specializing in digital learning design. The validation instrument was a four-point Likert-scale questionnaire ranging from 1 (very inappropriate) to 4 (very appropriate). The assessment covered five aspects: (a) alignment of syntax with PjBL principles, (b) clarity of project implementation guidelines, (c) integration of digital technology, (d) correspondence of content with scientific literacy indicators, and (e) interface design and media accessibility.

The validity score was calculated as a percentage of the obtained score relative to the maximum possible score. The validity criteria were 81–100% (very valid), 61–80% (valid), 41–60% (moderately valid), 21–40% (less valid), and ≤20% (invalid) (Salamah et al., 2022). The experts' quantitative assessments were analyzed descriptively, while their qualitative comments and suggestions were used to identify aspects requiring revision. The product was revised based on the experts' recommendations before being implemented in the field.

Instrument Development and Validation Procedures

The scientific literacy assessment instrument was developed through the following systematic procedures:

1. Construct Definition: The instrument was designed to measure three PISA 2022 scientific literacy competencies: (a) explaining phenomena scientifically, (b) evaluating and designing scientific investigations, and (c) interpreting data and evidence scientifically.
2. Blueprint Development: A test blueprint was created specifying the number of items for each competency and cognitive level, aligned with the environmental pollution content.
3. Item Writing: Twenty multiple-choice items with reasoning (reasoned objective test) were developed. Each item required students to select the correct answer and provide a written justification, allowing assessment of both factual knowledge and reasoning ability.
4. Content Validation: The draft instrument was reviewed by the same material expert who validated the learning model. Expert judgment was used to assess content relevance, clarity, and alignment with indicators. Items with validity scores below 75% were revised or replaced.
5. Pilot Testing: The instrument was piloted with 20 students from a different school (not involved in the main study) to assess item difficulty, discrimination index, and reliability. Items with discrimination index below 0.25 were revised, and items with difficulty index outside the $0.30 - 0.70$ range were adjusted.
6. Reliability Estimation: The internal consistency of the instrument was calculated using Cronbach's alpha. The instrument achieved a reliability coefficient of $\alpha = 0.82$, indicating good internal consistency.

The final instrument consisted of 20 validated items and was administered as a pretest and posttest to measure changes in students' scientific literacy following the implementation of the developed model.

Implementation Phase

The Implementation phase involved a limited field trial at MI Islamiyah Sumurgenuk during the even semester of the 2025/2026 academic year. The participants were 25 fourth-grade students selected through purposive sampling. The participants consisted of 13 female (52%) and 12 male (48%) students, aged 9 to 10 years. Based on school records, their prior science achievement ranged from 60 to 78, with an average of 68.5, indicating moderate prior knowledge. All students had access to a smartphone or tablet, and 92% reported using digital devices regularly for non-academic purposes.

The selection criteria were that the school had adequate digital learning infrastructure, including Wi-Fi, access to computers or mobile devices, and a teacher willing to collaborate in the implementation of the developed model. The fourth-grade students were selected because the environmental pollution topic was relevant to the science learning content at this level and could be implemented through project-based activities supported by digital technology.

The trial employed a one-group pretest–posttest design. This design was selected for the limited trial because the primary purpose of this stage was to obtain initial empirical evidence regarding the practicality and potential effectiveness of the newly developed model within an authentic classroom setting before broader implementation. The design consisted of a pretest (O_1), implementation of the digital-integrated PjBL model (X), and posttest (O_2): $O_1 - X - O_2$ (Levitt et al., 2018). Before the intervention, students completed the pretest to determine their initial level of scientific literacy. The students then participated in science learning on environmental pollution using the digital-integrated PjBL model for four meetings, with each meeting lasting 2 × 40 minutes. During implementation, the learning activities followed the developed PjBL syntax and incorporated the designated digital platforms and learning materials. After all learning activities were completed, the students completed the posttest using the same assessment instrument to measure changes in scientific literacy.

Practicality data were collected during and after the implementation. Two observers used a learning syntax implementation observation sheet to assess the extent to which the planned learning stages were implemented. In addition, students completed a response questionnaire after the learning process to provide information regarding the practicality and usability of the developed model from the learners' perspective.

The one-group pretest–posttest design was appropriate for this limited trial because the study at this stage emphasized preliminary testing of the developed product rather than establishing definitive causal effects. However, this design has methodological limitations because it does not include a control or comparison group. Therefore, changes between

pretest and posttest scores may be influenced by factors other than the intervention, such as maturation, testing effects, classroom experiences, or other external influences. The findings from this limited trial were consequently interpreted as preliminary evidence of the model's effectiveness rather than conclusive evidence of its causal impact. A controlled or quasi-experimental design involving a comparison group would be required in subsequent research to provide stronger evidence of causal effectiveness.

Evaluation Phase

The Evaluation phase involved the systematic analysis of data obtained from the validation and implementation stages to determine the validity, practicality, and effectiveness of the developed product. Product validity was determined from the expert validation questionnaire using the percentage-score formula. Practicality was assessed using two instruments: a student response questionnaire administered after the learning process and a learning syntax implementation observation sheet completed by two observers. The student response questionnaire employed a four-point Likert scale, and the practicality criteria were 81–100% (very practical), 61–80% (practical), 41–60% (moderately practical), 21–40% (less practical), and ≤20% (impractical) (Inayah & Iskandar, 2023).

The effectiveness of the developed model was examined by comparing students' scientific literacy scores before and after implementation. Because the number of participants was fewer than 50, the normality of the pretest and posttest data was assessed using the Shapiro–Wilk test (Field, 2018). When the data met the normality assumption, a paired-samples t-test was conducted to determine whether the difference between the pretest and posttest scores was statistically significant. In addition, the magnitude of students' improvement in scientific literacy was calculated using the normalized gain (N-gain) formula:

$$\boldsymbol{g} = \frac{(\boldsymbol{posttest\ score} - \boldsymbol{pretest\ score})}{(\boldsymbol{maximum\ score} - \boldsymbol{pretest\ score})}$$

The N-gain values were interpreted as follows: g > 0.7 indicated a high gain, $0.3 \leq g \leq 0.7$ indicated a medium gain, and $g < 0.3$ indicated a low gain. All quantitative analyses were performed using SPSS version 26.0.

Overall, the ADDIE procedure enabled the developed model to undergo a systematic process from needs identification and product design to expert validation, limited classroom implementation, and evaluation. The combination of expert validation, classroom observation, student responses, and pretest–posttest results provided complementary evidence regarding the feasibility and initial effectiveness of the digital-integrated PjBL model.

RESULT AND DISCUSSION

The developed digital-integrated Project-Based Learning (PjBL) model consists of six learning phases that systematically integrate digital technology with project-based science learning and scientific literacy objectives. The syntax was designed to ensure that digital technology functions not only as supplementary media but also as an integral component supporting inquiry, collaboration, project management, monitoring, communication, and reflection. The syntax of the developed model is presented in Table 1.

Table 1. Syntax of Digital-Integrated PjBL Model

Phase	Teacher–Student Activities	Digital Integration	Scientific Literacy Objectives
1. Determining Fundamental Questions	The teacher presents a video depicting a pollution phenomenon; students observe the content and formulate relevant questions.	YouTube, Quizizz	Explaining scientific phenomena
2. Project Design Planning	Students collaboratively develop a project framework, such as a digital poster, short video, or investigative report.]	Google Docs, Canva, Padlet	Designing scientific inquiry
3. Schedule Arrangement	The teacher and students mutually agree on a project timeline; students maintain a digital project journal.	Google Calendar, Trello	Managing scientific processes

4. Monitoring	The teacher monitors students' progress through discussion groups and provides constructive feedback.	Google Classroom, WA Group	Evaluating advancement
5. Outcome Assessment	Students present their project outputs, followed by question-and-answer activities and peer evaluation.	PowerPoint, Zoom/Google Meet, digital rubric	Communicating scientific findings
6. Experience Evaluation	Students reflect on their learning process, while the teacher evaluates the achievement of scientific literacy competencies	Google Forms	Reflecting on the learning experience

Table 1 shows that digital technology was integrated throughout all six phases of the developed PjBL model. Each digital platform served a specific instructional function, including identifying problems, planning projects, managing project schedules, monitoring progress, presenting findings, and conducting reflection. Thus, digital technology was positioned as an integral component of the learning process rather than merely as supplementary learning media.

Expert Validation Results

Product validation was conducted by two experts, namely a science learning material expert and a media/educational technology expert. The validation assessed the alignment of the model syntax with PjBL principles, the clarity of project implementation guidelines, the integration of digital technology, the correspondence between the content and scientific literacy indicators, and the interface design and media accessibility. The validation results are presented in Table 2.

Table 2. Validation Results of Digital-Integrated PjBL Model

Assessed Aspect	Subject Matter Expert (%)	Media Expert (%)	Mean Score (%)	SD	Category
Alignment of syntax with PjBL principles	90	86	88	2.83	Highly Valid
Clarity of project implementation guidelines	88	90	89	1.41	Highly Valid
Integration of digital technology	86	94	90	5.66	Highly Valid
Correspondence of content with scientific literacy indicators	92	–	92	–	Highly Valid
Interface design and media accessibility	–	96	96	–	Highly Valid
Overall mean	89	91,5	90,25	2.50	Highly Valid

The results presented in Table 2 show that the overall mean validation score was 90.25% (SD = 2.50), which was categorized as highly valid. The subject matter expert provided an overall score of 89%, while the media expert provided a score of 91.5%. At the aspect level, the mean scores ranged from 88% to 96%, indicating consistently high ratings across the assessed components. The highest mean score was obtained for interface design and media accessibility (96%), while the lowest was found for alignment of syntax with PjBL principles (88%). These results indicate that the developed digital-integrated PjBL model was considered appropriate in terms of instructional structure, content alignment, digital integration, and media accessibility.

The material expert suggested that project examples be made more diverse and contextual to the students' environment. Meanwhile, the media expert recommended simplifying access links using a linktree so that students do not have difficulty remembering many website addresses. Both suggestions have been revised before the trial.

These validation results are consistent with (Rahmawati et al., 2022) who emphasized that expert validation is a crucial step to ensure product feasibility and that valid PjBL learning devices must meet aspects of syntax suitability, clarity of guidelines, and media integration."

Practically Test Results

The practicality of the model was measured from two indicators: (1) student response questionnaires after participating in learning, and (2) syntax implementation observation sheets by two observers. The student response results are presented in Table 3.

Table 3. Student Response Questionnaire Results ($\boldsymbol{n = 25}$)

Statement	Mean Score	SD	Percentage (%)	Category
The digital PjBL model is easy to comprehend and follow	3,53	**0, 51**	88,3%	Highly Practical
The digital platforms employed are readily accessible	3,47	0,65	86,8%	Highly Practical
The assigned projects are engaging and pertinent	3,66	0,48	91,5%	Highly Practical
Team collaboration proceeds smoothly with digital assistance	3,50	0,55	87,5%	Highly Practical
This model facilitates understanding of environmental pollution topics	3,59	0,50	89,8%	Highly Practical
Overall mean	3,55	0,54	88,8%	Highly Practical

Based on Table 3, the overall student response obtained a mean score of 3.55 (SD = 0.54), corresponding to 88.8%, and was categorized as highly practical. At the statement level, the percentage scores ranged from 86.8% to 91.5%. The highest percentage was obtained for the statement "The assigned projects are engaging and pertinent" (91.5%; mean = 3.66; SD = 0.48). This result indicates that students perceived the project activities as interesting and relevant to their learning experiences. Meanwhile, the lowest percentage was obtained for "The digital platforms employed are readily accessible" (86.8%; mean = 3.47; SD = 0.65). The lower score on this item was related to internet signal interference experienced by some students when accessing tutorial videos.

The other statements also received high ratings. Students reported that the digital PjBL model was easy to comprehend and follow (**88.3%; mean = 3.53; SD = 0.51**), team collaboration proceeded smoothly with digital assistance (**87.5%; mean = 3.50; SD = 0.55**), and the model facilitated understanding of environmental pollution topics (**89.8%; mean = 3.59; SD = 0.50**). These findings demonstrate that the model was generally perceived as accessible, engaging, and supportive of collaborative learning.

The results of the syntax implementation observation showed that of the six planned PjBL phases, the average implementation reached **91.7%**, categorized as **very good**. The monitoring and evaluation phase was implemented at **100%**, while the schedule arrangement phase reached **83.3%** because two groups were late in filling out the digital journal.

These findings support the statement of (Handayani & Haryati, 2024) that digital integration in PjBL can increase student ease and motivation, although the availability of internet infrastructure remains a determining factor. (Jamilah et al., 2024) also reported similar findings that technical obstacles such as signal and device availability remain challenges in implementing digital PjBL in areas with limited access.

Effectivities Test Results

The effectiveness of the model was measured by comparing students' scientific literacy scores before and after the implementation of the digital-integrated PjBL model. Descriptive statistics, normality results, and the paired-samples t-test are presented in Table 4.

Table 4. Descriptive Statistics, Normality Test, and Paired t-Test Results for Students' Scientific Literacy ($n = 25$)

Variable	N	Mean	SD	Min	Max	Shapiro-Wilk (Sig.)	Normality
Pretest	25	61,48	4,08	54	70	0,152	Normal ($p > 0{,}05$)
Posttest	25	85,20	3,39	79	92	0,208	Normal ($p > 0{,}05$)
Gain (Posttest-Pretest)	25	23,72	1,06	–	–	–	–
Paired t-Test		$t = 112$	$df = 24$	$Sig.(2-tailed) = 0{,}000$	Mean Difference = 23,72	Std. Error Diff = 0,21	95 % CI (23,29 – 24,15)

As shown in Table 4, the mean pretest score was **61.48 (SD = 4.08)**, with scores ranging from **54 to 70**, whereas the mean posttest score increased to **85.20 (SD = 3.39)**, with scores ranging from **79 to 92**. Thus, the mean score increased by **23.72 points** after the implementation of the digital-integrated PjBL model.

The Shapiro-Wilk test indicated that both the pretest and posttest data were normally distributed, with significance values of **0.152** and **0.208**, respectively. Since both values were greater than 0.05, the normality assumption was satisfied, and a paired-samples t-test was subsequently conducted.

The paired-samples t-test showed a statistically significant difference between the pretest and posttest scores (**t = 112, df = 24, p < 0.001**). The mean difference was **23.72**, with a standard error difference of **0.21** and a **95% confidence interval ranging from 23.29 to 24.15**. These results indicate a statistically significant improvement in students' scientific literacy scores following the implementation of the digital-integrated PjBL model.

To further examine the magnitude of the improvement, an N-gain analysis was conducted. The mean N-gain was **0.616**, which falls within the **medium** category based on the N-gain interpretation criteria. Thus, although the improvement was statistically significant, its magnitude was moderate rather than high.

The improvement in students' scientific literacy can be explained by several characteristics of the developed model. First, the digital-integrated PjBL model encourages

active and contextual learning. At the fundamental-question stage, students were invited to analyze video footage about river pollution in their area. This activity trains the indicator of explaining phenomena scientifically because students must identify the causes, impacts, and causal relationships of pollution. This is in line with the theory of experiential learning from (Kolb, 2014), which states that meaningful learning occurs when students are directly involved in real experiences and reflect on them. The application of this theory in a digital environment can be facilitated through online simulations and structured reflection activities (Jong et al., 2025).

Second, the use of digital platforms such as Google Docs and Padlet allows broader collaboration and access to information. During project design, students can search for secondary data, news articles, or previous research related to environmental pollution. The ability to evaluate the credibility of information sources is an important part of the indicator of evaluating and designing scientific investigations (Bo & W., 2023).

Third, the monitoring process conducted by the teacher through Google Classroom provides opportunities for timely feedback. Students can identify weaknesses in their projects and make improvements before the presentation stage. Fast and specific feedback has proven effective in improving conceptual understanding (Hattie & Timperley, 2007). This finding is consistent with feedback models that highlight the importance of feedback at the task and process level (Leong et al., 2025).

Fourth, the project presentation and evaluation stage provides opportunities for students to interpret data and evidence scientifically and communicate their findings Students are asked to present observational data, such as water turbidity levels, pH, or the amount of waste, in the form of graphs or tables and then explain their conclusions. This ability is one of the competencies that is still low among Indonesian students based on PISA 2022 results (Widowati et al., 2017).

The findings of this study are in line with the report of Zendrato et al., (2024) that PjBL is effective in improving scientific literacy with an N-gain of 0.58 (medium category). In the present study, an N-gain of **0.616** was obtained, which also remained within the medium category. The result extends previous findings by demonstrating how digital technology can be systematically incorporated across the PjBL syntax rather than being used only as presentation media. In the developed model, digital technology was used for initial assessment through Quizizz, collaboration through Google Docs, project monitoring through Google Classroom, and reflection through Google Forms. This is consistent with the recommendation of (Rahmawati et al., 2022) that PjBL in the digital era needs to be

designed as an integrated system rather than simply attaching technology to one or two learning stages.

The contribution of the developed model therefore lies not only in combining PjBL with digital technology, but in structuring the relationship between each PjBL phase, the digital tool used, and the targeted scientific literacy competency. This integration provides a more systematic framework for teachers to guide students from identifying authentic problems through project planning, investigation, monitoring, communication, and reflection.

In addition, the selection of environmental pollution material is based on its highly contextual nature and its accessibility to students' everyday experiences. Students can connect scientific concepts, such as pollution indicators, ecological impacts, and remediation efforts, with phenomena they encounter in their environment. Such contextuality can support retention and knowledge transfer. (Handayani & Haryati, 2024) emphasized that meaningful science learning must be able to connect subject matter with students' life experiences.

Nevertheless, the effectiveness findings need to be interpreted within the methodological limitations of the study. The trial was conducted in only one school with adequate digital facilities, so the findings may not be directly generalizable to schools with limited internet access or different technological conditions. In addition, the one-group pretest-posttest design did not include a control group, meaning that factors such as student motivation, maturation, testing effects, or other classroom experiences could not be fully controlled. The implementation was also limited to four meetings, which may not be sufficient to determine the long-term development of scientific literacy. Therefore, the current findings provide evidence of improvement following implementation, but they should not be interpreted as definitive causal evidence.

Further research should employ a quasi-experimental design with a comparison group to provide stronger evidence regarding effectiveness. Future studies could also examine the model across different science topics, educational levels, and school contexts, particularly schools with varying levels of digital infrastructure. Further research can also explore this model in a blended learning context (Nabilah et al., 2025).

Discussion

The findings demonstrate that the digital-integrated PjBL model developed through the ADDIE procedure exhibits high validity, strong practicality, and moderate effectiveness in improving students' scientific literacy on environmental pollution. However, the

moderate N-gain (0.616) is not an indication of insufficient effectiveness; rather, it reflects the inherent complexity of scientific literacy as a higher-order competency that develops gradually. While these results align with previous research on PjBL effectiveness, they extend existing knowledge by providing empirical evidence that systematic digital integration across all PjBL syntax phases yields measurable improvements in scientific literacy competencies.

The improvement in students' scientific literacy, indicated by a significant increase from pretest (M = 61.48, SD = 4.08) to posttest (M = 85.20, SD = 3.39) scores (t = 112, df = 24, $p < 0.001$) and an N-gain of 0.616 (medium category), warrants careful interpretation. This improvement (approximately 38.6%) is notable when compared to previous studies. (Zendrato et al., 2024) reported an N-gain of 0.58 for PjBL implementation without systematic digital integration, while (Yuniasih et al., 2022) found improvements in science process skills but did not specifically measure PISA-aligned scientific literacy competencies. The slightly higher N-gain obtained in the present study (0.616) suggests that systematic digital integration provides added value beyond conventional PjBL approaches.

The novelty of this study lies in how digital technology was strategically embedded within each learning phase rather than used merely for presentation purposes. Digital platforms served distinct instructional functions: Quizizz for initial assessment and problem identification, Google Docs and Padlet for collaborative project planning, Google Calendar for schedule management, Google Classroom for continuous monitoring and feedback, and Google Forms for structured reflection. This systematic integration addresses the gap identified by (Anggraini, 2025) namely, the insufficient integration of digital technology throughout the entire PjBL learning process. The present study thus contributes a structured framework that demonstrates how each digital platform aligns with specific scientific literacy competencies, consistent with the recommendation of Rahmawati et al., (2022) that PjBL in the digital era needs to be designed as an integrated system rather than simply attaching technology to one or two learning stages.

Several factors may explain why the present findings extend previous research. First, the selection of environmental pollution as the content area provided a highly contextual phenomenon for students to investigate. This contextual relevance likely strengthened the connection between scientific concepts and students' everyday experiences, thereby enhancing retention and knowledge transfer. Handayani & Haryati, (2024) emphasized that meaningful science learning must connect subject matter with students' life experiences, and the present study provides empirical support for this assertion within a digitally enhanced PjBL framework.

Second, the monitoring and feedback mechanisms enabled by digital technology (100% implementation of the monitoring phase) likely contributed to the effectiveness findings. Unlike conventional PjBL implementations where teachers may struggle to provide timely feedback to all groups, the digital platforms enabled continuous monitoring and specific, actionable feedback. Hattie & Timperley (2007) established that fast and specific feedback is effective in improving conceptual understanding. This finding is consistent with Leong et al. (2025), who highlighted the importance of feedback at the task and process level. In the context of scientific literacy, feedback helps students revise misconceptions about scientific methods and data interpretation.

Third, the alignment between learning activities and PISA 2022 scientific literacy indicators—explaining phenomena scientifically, designing investigations, and interpreting data and evidence—represents a deliberate design feature distinguishing this model from previous implementations. The subject matter expert validation score of 89% for content alignment with scientific literacy indicators confirms the model's integration of these competencies throughout the learning process, supporting the assertion of Ayu et al., (2025) that learning activities must align with PISA scientific literacy indicators.

The medium category N-gain (0.616) rather than high category (> 0.7) requires discussion. Several explanations are possible. First, the implementation duration (four meetings of 2 × 40 minutes) may have been insufficient to achieve higher gains in scientific literacy, which is a complex competency requiring sustained practice. This is consistent with (Fadlurrahman et al., 2026) observation that scientific literacy develops through prolonged engagement with scientific practices rather than short-term interventions. Second, the participants were fourth-grade students (approximately 9-10 years old) for whom some scientific literacy competencies, particularly evaluating information and evidence, may be developmentally challenging. Third, the one-group pretest-posttest design without a control group may have introduced testing effects or other confounds that influenced the results, as noted by Levitt et al. (2018).

The high practicality ratings from students (88.8%) and observers (91.7%) indicate that the model is feasible for classroom implementation, provided that adequate digital infrastructure is available. The lowest-rated student response item—"The digital platforms employed are readily accessible" (86.8%)—highlights the importance of considering internet connectivity and device availability. This is consistent with (Jamilah et al., 2024) finding that technical obstacles such as signal and device availability remain significant challenges in implementing digital PjBL in areas with limited access.

The model's practicality also suggests that teachers can implement the structured syntax with relative ease, particularly because each phase includes specific digital tools and clear guidelines. This addresses a common concern in PjBL implementation—namely, the time and expertise required to manage project-based learning effectively. By providing a systematic framework with embedded digital support, the model reduces the cognitive load on teachers and enables them to focus on facilitating student learning, as emphasized by Silvester et al. (2024) regarding the importance of digital competence for teachers in technology-based learning.

Methodological Considerations and Future Research

The methodological limitations must be acknowledged. The one-group pretest-posttest design, while appropriate for a limited trial of a newly developed product, does not control for threats to internal validity such as maturation, history, testing effects, or regression to the mean (Levitt et al., 2018). It is therefore possible that factors other than the intervention contributed to the observed improvements. Additionally, the limited trial involved only one school with adequate digital infrastructure, which may limit generalizability to schools with different technological conditions, as noted by Sharma (2017) regarding sampling technique considerations.

Future research should employ quasi-experimental designs with control groups, larger sample sizes, and diverse school contexts to provide stronger evidence regarding the model's causal effectiveness (Levitt et al., 2018). Studies could also investigate whether effectiveness varies across different scientific literacy competencies and explore the model's application in blended learning contexts (Nabilah et al., 2025), as well as test the model on various science topics and different educational levels (Salamah et al., 2022).

In conclusion, the digital-integrated PjBL model demonstrates promise for improving students' scientific literacy while addressing the practical need for structured, technology-enhanced science instruction. The model's novelty lies in systematically integrating digital platforms across all syntax phases and explicitly aligning them with scientific literacy competencies. This systematic approach extends previous research by demonstrating how digital tools can operationalize experiential learning theory (Kolb, 2014) and feedback mechanisms (Hattie & Timperley, 2007) within project-based science learning. The moderate effectiveness finding, while encouraging, highlights the need for continued research to refine the model and investigate its effects across diverse contexts, particularly considering infrastructure readiness before wider implementation Jong et al., (2025);OECD, (2023).

CONCLUSIONS AND SUGGESTIONS

The digital-integrated PjBL model developed in this study offers a systematic framework for enhancing scientific literacy in elementary science education through the strategic integration of digital technology across all six PjBL syntax phases. Unlike conventional implementations where technology serves only as supplementary media, this model embeds digital platforms throughout the entire learning process—from problem identification and collaborative planning to monitoring, presentation, and reflection—with each phase explicitly aligned to specific scientific literacy competencies. Beyond immediate learning outcomes, the model cultivates essential 21st-century competencies including critical thinking, collaboration, communication, and digital literacy, while addressing the persistent challenges in Indonesian students' scientific literacy as identified in PISA 2022. The selection of locally relevant topics such as environmental pollution further demonstrates how contextual learning can strengthen students' ability to explain phenomena, design investigations, and interpret evidence.

For future research, quasi-experimental studies with control groups are recommended to establish stronger causal evidence of the model's effectiveness. Further investigations should examine the model's applicability across diverse science topics, educational levels, and school contexts with varying digital infrastructure. Additionally, exploring the model's integration within blended learning environments and conducting longitudinal studies would provide valuable insights into its long-term impact and adaptability to hybrid instructional settings.

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