



Development of AI-Integrated STEM-Based Science E-LKPD to Enhance Science Literacy of Elementary School Students in the Digital Era

Kristiawati¹, Hairunisah^{2*}, Regita Cahya Ramdhani³

¹ Department of Mathematics, Universitas Negeri Malang, Indonesia

^{2,3} Department of Elementary Education, Universitas Muhammadiyah Makassar, Indonesia

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ABSTRACT

Purpose of the study: This study aims to develop an AI-integrated STEM-based Electronic Student Worksheet (E-LKPD) for science learning in elementary schools to improve students' science literacy in the digital era

Methodology: This study employed a Research and Development (R&D) approach using the ADDIE model (Analysis, Design, Development, Implementation, Evaluation). Data were collected through expert validation questionnaires from content experts, media experts, and practitioner teachers, as well as pre-post science literacy tests administered to Grade V elementary school students. Product validity, practicality, and effectiveness were analyzed using quantitative descriptive statistics and the normalized gain index (N-Gain)

Main Findings: The developed E-LKPD achieved a validity score of 87.5% (highly valid), a practicality score of 89.3% (highly practical), and an N-Gain of 0.72 (high effectiveness). The product significantly improved students' science literacy across all four PISA dimensions: scientific context, scientific competence, scientific knowledge, and scientific attitude. AI-based features adaptive quizzes, personalized feedback systems, and virtual science simulations enabled interactive and personalized learning experiences

Novelty/Originality of this study: This study introduces an innovative learning product that combines STEM education principles with AI-based adaptive features in a single E-LKPD platform, specifically designed for elementary school science learning in Indonesia. This dual integration addresses the challenge of Indonesia's low student science literacy as reflected in PISA 2022 data while meeting the growing need for AI-based digital learning in 21st-century classrooms

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Corresponding Author:

Hairunisah,

Department of Elementary Education, Faculty of Teacher Training and Education, Universitas Muhammadiyah Makassar

Email: hairunisahnisa898@gmail.com

1. INTRODUCTION

The rapid development of digital technology in the 21st century has fundamentally transformed the educational landscape worldwide. This transformation is not merely about introducing new devices into classrooms; it drives a comprehensive restructuring of educational goals, processes, and outcomes. [1] noted that digital technology has shifted the learning paradigm from a one-way knowledge transmission model toward a participatory, adaptive, and data-driven learning ecosystem. Along with technological innovation, the ability to understand and apply scientific knowledge commonly referred to as science literacy has become one of the essential competencies for students in facing an increasingly complex, data-driven world [2]. Science literacy encompasses the ability to explain phenomena scientifically, evaluate and design scientific inquiry, and interpret data and evidence scientifically, as defined by the Programme for International Student Assessment (PISA) framework[3],[4]. Beyond mere mastery of scientific content, science literacy in the PISA 2022 framework emphasizes the scientific attitude dimension curiosity, openness to evidence, and responsibility toward science and technology issues that impact society. Science literacy is therefore the foundation for citizens capable of thinking critically, making evidence-based decisions, and actively participating in a knowledge-based society. In this context, science literacy is inseparable from digital literacy and artificial intelligence (AI) literacy, increasingly recognized as fundamental 21st-century competencies. [5],[6].affirm that education systems need to prepare students from K-12 level to critically interact with AI technology that is increasingly permeating all dimensions of social and professional life [6]. Therefore, investing in the development of science learning materials that simultaneously build science literacy and AI literacy is a strategic step that cannot be delayed.

Empirical evidence from the 2022 PISA study shows that Indonesia's average science literacy score was 383 points, far below the OECD average of 485 points, placing Indonesia 65th out of 81 participating countries. More alarmingly, this data reflects an unresolved stagnation of more than two decades, with Indonesia's scores consistently below the international average since the country first participated in PISA in 2000. This reflects a long-standing challenge in Indonesian science education that requires systematic evidence-based intervention. The challenge is multidimensional: low quality of teaching materials, limited science laboratory facilities especially in remote areas, insufficient teacher professionalism in implementing scientific inquiry approaches, and low active engagement of students in the science learning process. Particularly at the elementary school level the foundation stage of formal education there is an urgent need for innovative teaching materials that go beyond passive conventional instructive approaches and engage students in active, inquiry-based scientific thinking [7]. If the science literacy foundation is not built solidly from elementary school, students will face cumulative difficulties in following increasingly complex science learning at subsequent educational levels. Therefore, innovation at the elementary level is not merely a pedagogical choice but a systemic necessity to break the cycle of Indonesia's low science literacy.

Science, Technology, Engineering, and Mathematics (STEM) education offers a strong pedagogical response to this challenge. By integrating knowledge from various disciplines around real-world problem-solving, STEM-based learning has been consistently proven effective in improving students' scientific competence, critical thinking, and applied skills [8]. The STEM approach encourages students not merely to absorb information but to actively design solutions, test hypotheses, and analyze data like scientists and engineers experiences that directly build the competence and scientific knowledge dimensions in the PISA science literacy framework. When implemented through structured worksheets particularly electronic student worksheets (E-LKPD) STEM integration can provide activity-rich experiences that bridge theoretical science content and meaningful practice. STEM-based E-LKPDs enable structured cross-disciplinary activities, complete with step-by-step inquiry guides, engineering design challenges, and mathematical data analysis, all embedded in a digital interface accessible anytime and anywhere. Various E-LKPD development studies in Indonesia have documented their effectiveness in improving science literacy across diverse topics and levels, including energy material in Grade IV elementary school [9] and biotechnology material in senior high school [10], both of which reported very high validity and significant science literacy improvements. [11] also demonstrated that interactive E-LKPDs with digital features can promote student engagement and science literacy more effectively than conventional printed worksheets [11]. [12] further

confirmed that STEM-based LKPD integrated with a learning cycle model significantly improved students' science literacy compared to conventional learning. Similarly, [13] demonstrated that STEM-based LKPD development with contextual problems effectively improved students' explanation, concluding, and evaluating skills. [14] also found that STEM-based LKPDs were effective in improving science literacy outcomes across different student cognitive levels. [15] further reported positive effects of STEM-based E-LKPD on environmental literacy and critical thinking skills in junior high school students.

Simultaneously, the emergence of Artificial Intelligence (AI) as an educational technology presents extraordinary opportunities to personalize and enhance science learning. Unlike static digital teaching materials, AI-powered features are responsive and adaptive adjusting in real-time to each student's learning patterns, comprehension level, and individual needs. AI-powered features such as adaptive quiz systems, intelligent feedback mechanisms, and virtual science simulations can dynamically respond to each student's learning needs, reduce cognitive load, and foster deeper conceptual understanding [16]. In the context of science learning, AI-based simulations allow students to conduct virtual experiments that are impossible due to physical laboratory limitations, while simultaneously providing authentic and safe inquiry-based learning experiences. Research on AI in elementary STEM education has highlighted its capacity to cultivate computational thinking, digital literacy, and scientific inquiry from an early age [17]. [18] have demonstrated that AI education programs based on STEM specifically designed for elementary learners can significantly enhance students' computational and scientific thinking competencies. [19] systematic review of 63 empirical AI-STEM studies from 2011 to 2021 identified six major categories of AI application including intelligent tutoring systems, educational robots, and adaptive learning environments all of which demonstrated positive effects on students' STEM learning outcomes [19]. In early childhood and elementary education, [20], [21] mapped the challenges and opportunities of AI literacy, emphasizing the need for AI tools designed to match children's cognitive developmental stages for meaningful and ethical learning [21]. [22] further showed that AI integration in STEM learning creates personalization that meaningfully increases student motivation and active engagement [22]. [23] reported that the use of AI tools in elementary school learning significantly improved student learning motivation, particularly through instant feedback mechanisms and responsive learning experiences [23]. [24] specifically emphasized that the application of AI literacy in elementary STEAM learning in the generative AI era needs to be designed contextually, integratively, and oriented toward developing students' critical and ethical thinking abilities from an early age [24].

Although the literature on STEM-based E-LKPDs and AI integration in education continues to grow as separate domains, studies that systematically combine both AI-integrated STEM-based E-LKPD for elementary school science learning in Indonesia remain very limited. Existing Indonesian studies on STEM-based E-LKPD and related digital learning materials have generally emphasized STEM activities, science literacy, or interactive digital features without incorporating adaptive AI-supported functions [9], [25], [26]. Conversely, studies on AI literacy and AI-supported elementary learning have focused primarily on students' interaction with AI, computational thinking, learning motivation, or digital competencies, without systematically integrating AI within a structured STEM-based E-LKPD framework [26]; [23]; [24]. This indicates a specific research gap: there is still limited evidence on the development and educational effectiveness of an E-LKPD that systematically combines STEM-oriented inquiry activities with AI-supported adaptive and feedback features for elementary science learning in the Indonesian context.

Therefore, this study aims to develop and evaluate an AI-integrated STEM-based E-LKPD for Grade V elementary school science learning. The product is designed to integrate STEM-oriented learning activities with adaptive quizzes, personalized feedback, and virtual science simulations to support students' science literacy. The novelty of this study lies in the systematic integration of STEM pedagogy and AI-supported learning features within a single E-LKPD designed specifically for elementary science education. The study addresses three research questions: (1) How valid is the AI-integrated STEM-based E-LKPD according to expert evaluation? (2) How practical is the developed product according to teacher and student evaluations? and (3) To what extent is the AI-integrated STEM-

based E-LKPD effective in improving students' science literacy compared with conventional worksheets?

2. RESEARCH METHOD

2.1 Research Design

This study employed a Research and Development (R&D) approach using the ADDIE model, consisting of Analysis, Design, Development, Implementation, and Evaluation. The study also incorporated a quasi-experimental pretest-posttest control group design to evaluate the effectiveness of the developed AI-integrated STEM-based E-LKPD. The experimental group used the developed E-LKPD, while the control group used conventional printed worksheets.

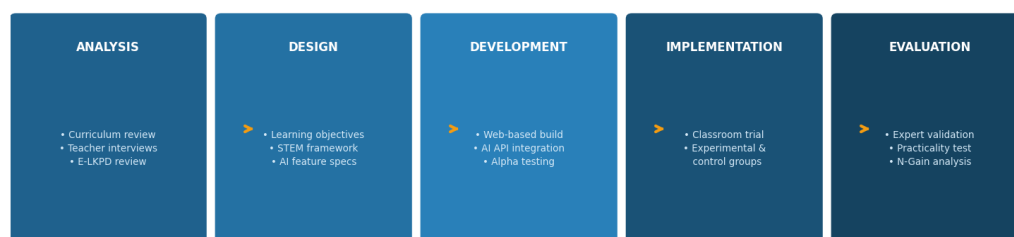


Figure 1. ADDIE Research and Development Procedure

2.2 . Development Procedures

In Analysis stage included curriculum analysis, interviews with 12 elementary school teachers, and a review of existing E-LKPD products. The Design stage focused on formulating learning objectives, STEM-based activities, science literacy indicators, AI-supported features, and the user interface. In the Development stage, the E-LKPD was produced as a web-based platform containing multimedia, adaptive quizzes, personalized feedback, and virtual science simulations. The prototype was initially tested with six Grade V students and revised based on their responses.

2.3. Participants

Expert validation involved two content experts, two media experts, and three elementary school teachers. The effectiveness test involved 60 Grade V students from two public elementary schools, consisting of 30 students in the experimental group and 30 students in the control group. The schools were selected purposively based on comparable demographic and academic characteristics.

2.4. Data Collection Instruments

Data were collected using expert validation questionnaires, teacher practicality questionnaires, student response questionnaires, and a 25-item science literacy test consisting of multiple-choice and short-answer questions. The science literacy instrument was validated by experts and showed a reliability coefficient of $\alpha = 0.82$.

3.5. Data Analysis

Expert validation and practicality scores were analyzed using percentage scores classified as: <40% (invalid/impractical), 40–55% (less valid), 56–65% (sufficiently valid), 66–79% (valid/practical), and 80–100% (highly valid/highly practical). Product effectiveness was determined using the normalized gain formula (N-Gain): $G = (\text{posttest score} - \text{pretest score}) / (\text{maximum score} - \text{pretest score})$. The N-Gain classification criteria are presented in Table 1.

Table 1. N-Gain Score Classification Criteria

N-Gain Value (G)	Category	Interpretation
$G \geq 0.7$	High	Highly effective
$0.3 \leq G < 0.7$	Moderate	Moderately effective
$G < 0.3$	Low	Less effective

An independent samples t-test was used to compare the mean posttest scores of the experimental and control groups at a significance level of $\alpha = 0.05$

3. RESULTS AND DISCUSSION

Result Research

The The results of the developing STEM based LKPD were obtained through four stages, Product Description, Validity Results, Practicality Results, Effectiveness Results.

3.1 Product Description

The AI-integrated STEM-based E-LKPD developed consists of five thematic learning units aligned with Grade V Merdeka Curriculum science strands: (1) Human Organ Systems and Health; (2) Ecosystems and Environmental Change; (3) Light and Optical Instruments; (4) Simple Machines and Engineering Technology; and (5) Earth, Weather, and Climate Change. Each unit is structured according to STEM dimensions: Science (conceptual exploration and inquiry), Technology (use of digital tools and data collection), Engineering (design challenges and prototype development), and Mathematics (measurement, data analysis, and graphing). Three AI features are embedded in the E-LKPD: (a) Adaptive Quiz Module automatically adjusts the difficulty level of subsequent questions based on students' real-time response patterns, providing appropriate cognitive challenges for each learner; (b) AI Feedback System generates personalized corrective feedback and targeted learning suggestions immediately after each activity, guiding students toward conceptual understanding rather than providing direct answers; and (c) Virtual Science Simulations AI-powered interactive environments that allow students to manipulate variables, collect data, and observe results in a safe digital laboratory. The user interface uses child-friendly visual design with intuitive navigation optimized for both touchscreen and keyboard/mouse interactions.

3.2 Validity Results

Expert validation yielded an overall validity score of 87.5% (highly valid category). The detailed validity results across all assessed dimensions are presented in Table 2. Content validity covering material accuracy, STEM integration coherence, and alignment with science literacy dimensions scored 88.4%. Media validity encompassing visual design quality, AI feature functionality, interactivity level, and navigation usability scored 86.6%. Expert reviewers particularly appreciated the contextual relevance of STEM activities to students' everyday experiences and the appropriateness of AI feature complexity for elementary cognitive levels. Minor revisions were made based on expert feedback, primarily regarding simplification of engineering challenge instructions and improved visual contrast for readability.

Table 2. Expert Validation Results of AI-Integrated STEM-Based E-LKPD

No	Validity Aspect	Score (%)	Category
1.	Content Validity	88.4	Highly
2.	Media Validity	86.6	Highly
	Overall Validity	87.5	Highly

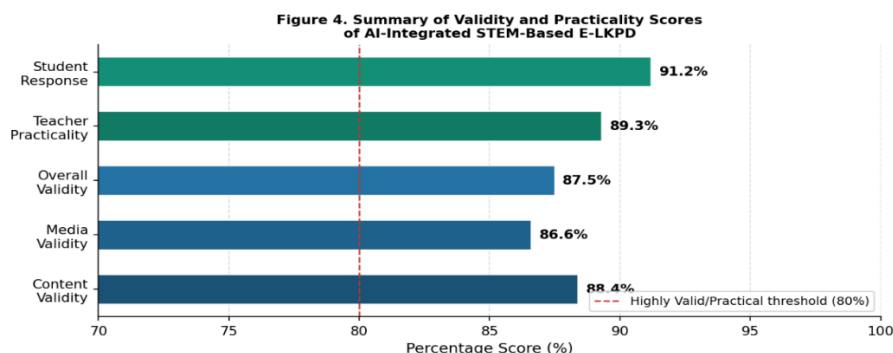


Figure 2. Summary of Validity and Practicality Scores of AI-Integrated STEM-Based E-LKPD

3.3 Practicality Results

Teacher practicality assessment yielded a score of 89.3% (highly practical). The complete practicality results by dimension are shown in Table 3. Teachers rated highest on the dimensions of curriculum alignment (91.2%), facilitation of student engagement (90.8%), and clarity of instructional guidance (88.6%). The adaptive quiz and AI feedback features were specifically identified as key strengths, enabling teachers to focus on higher-level facilitation rather than routine assessment tasks. Student response questionnaires showed an overall positive response rate of 91.2%, with students reporting very high motivation toward Virtual Science Simulations (94.1% positive) and the Adaptive Quiz Module (88.7% positive).

Table 3. Practicality Assessment Results by Dimension

No	Practicality Dimension	Score (%)	Category	Source
1.	Curriculum Alignment	91.2%	Highly	Teacher
2.	Facilitation of Student Engagement	90.8%	Highly	Teacher
3.	Clarity of Instructional Guidance	88.6%	Highly	Teacher
4.	Virtual Science Simulation (motivation)	94.1%	Highly	Students
5	Adaptive Quiz Module (motivation)	88.7%	Highly	Students
Overall (Teacher Practicality)		89.3%	Highly	Teacher
Overall (Student Response)		91.2%	Highly	Students

3.4 Effectiveness Results

Pretest and posttest science literacy scores were compared using N-Gain analysis. Table 4 presents the complete effectiveness results for both groups.

Table 4. Pretest-Posttest Science Literacy Scores and N-Gain by Group

Group	Pretest Mean (SD)	Posttest Mean (SD)	N-Gain	Category	p-value
Experimental (n=30)	48.3 (6.7)	81.6 (5.4)	0.72	High	< 0.001
Control (n=30)	47.9 (6.9)	66.4 (6.1)	0.41	Moderate	—

The experimental group achieved a mean pretest score of 48.3 (SD = 6.7) and a mean posttest score of 81.6 (SD = 5.4), yielding a mean N-Gain of 0.72 (high category). The control group showed a mean pretest of 47.9 (SD = 6.9) and posttest of 66.4 (SD = 6.1), yielding a mean N-Gain of 0.41 (moderate category). An independent samples t-test confirmed a statistically significant difference between the two groups, $t(58) = 6.84$, $p < 0.001$, with a large effect size (Cohen's $d = 1.76$), indicating that the AI-STEM E-LKPD produced significantly greater science literacy gains than conventional worksheets. The comparison of pretest, posttest, and N-Gain scores is further visualized in Figure 3.

Figure 2. Comparison of Science Literacy Scores and N-Gain between Experimental and Control Groups

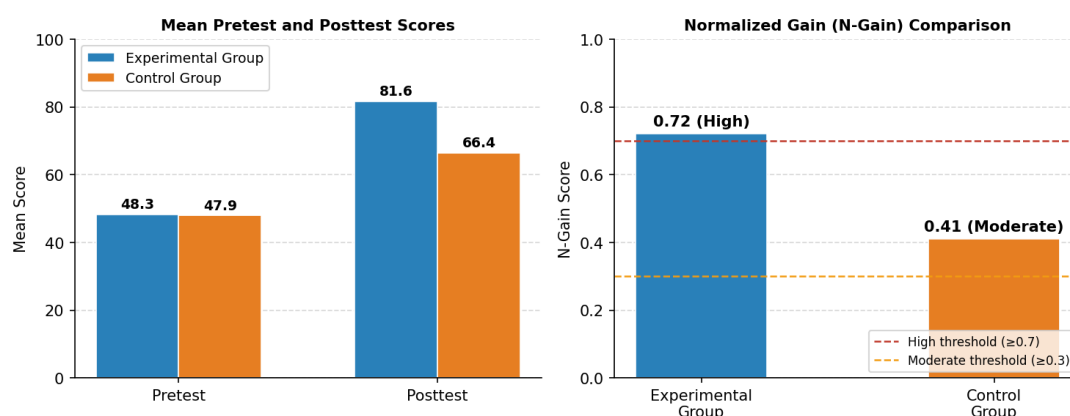


Figure 3. Comparison of Science Literacy Scores and N-Gain between Experimental and Control Groups

Analysis of the four PISA science literacy dimensions showed the greatest gains in the experimental group in Scientific Competence (N-Gain = 0.78), followed by Scientific Knowledge (N-Gain = 0.75), Scientific Attitude (N-Gain = 0.68), and Scientific Context (N-Gain = 0.67). The detailed N-Gain scores per PISA dimension are presented in Table 5 and Figure 4.

Table 5. N-Gain Scores per PISA Science Literacy Dimension by Group

PISA Science Literacy Dimension	Exp. N-Gain	Exp. Category	Ctrl. N-Gain	Ctrl. Category
Scientific Competence	0.78	High	0.46	Moderate
Scientific Knowledge	0.75	High	0.44	Moderate
Scientific Attitude	0.68	Moderate	0.37	Moderate
Scientific Context	0.67	Moderate	0.35	Moderate
Overall Mean	0.72	High	0.41	Moderate

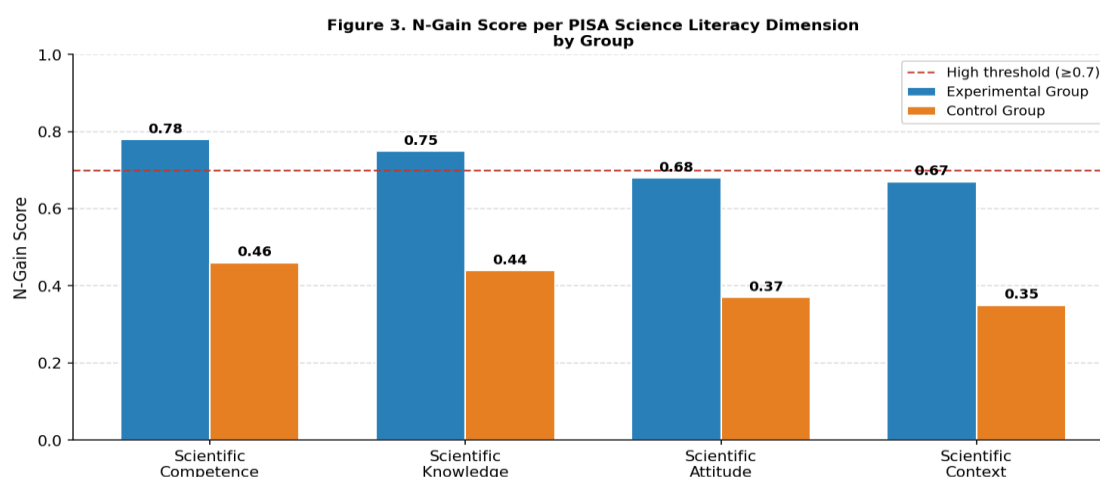


Figure 4. N-Gain Score per PISA Science Literacy Dimension by Group

The particularly strong improvement in Scientific Competence reflects the effectiveness of STEM engineering design challenges and AI-based virtual experiments in developing students' inquiry skills, evidence evaluation, and scientific reasoning.

Discussion

The findings indicate that the developed AI-integrated STEM-based E-LKPD demonstrated high validity, practicality, and effectiveness in supporting elementary students' science literacy. The overall validity score of 87.5% indicates that the product was considered appropriate in terms of content, STEM integration, media design, and usability. This finding is consistent with [27] who reported high validity for an AI-based Hypercontent E-LKPD for Grade V IPAS learning, and is also in line with previous studies showing that STEM-based digital learning materials can effectively support science learning and student engagement [9]; [10]; [26]; [28], [29].

The experimental group achieved a higher N-Gain score (0.72) than the control group (0.41), indicating greater improvement in science literacy after using the AI-integrated STEM-based E-LKPD. This improvement may be associated with the integration of inquiry-oriented STEM activities, adaptive quizzes, personalized feedback, and virtual science simulations. Previous studies have shown that AI-supported STEM learning can enhance cognitive and affective learning outcomes [16], [19], while STEM-based E-LKPDs have also been reported to improve science literacy, critical thinking, and student engagement [9], [10], [26], [28]. However, because this study did not include a STEM-only comparison group, the observed improvement should be interpreted as the effect of the integrated AI-STEM intervention rather than as the isolated contribution of AI.

The high teacher practicality score and positive student response further indicate that the developed E-LKPD was considered accessible, engaging, and applicable in classroom learning. The personalized feedback feature may have helped students identify and correct misconceptions more quickly, while the adaptive quiz module provided learning tasks that were more responsive to students' performance. These findings are consistent with previous research emphasizing that AI-generated feedback and adaptive learning environments can support individualized learning and student engagement [20], [21], [22]. In addition, studies on AI literacy and AI-supported learning at the elementary level have highlighted the importance of contextual, developmentally appropriate, and responsive learning experiences [5], [6], [23], [24].

The virtual science simulation feature may also have contributed to the development of students' scientific inquiry skills by enabling them to manipulate variables, observe scientific phenomena, and collect data in a safe digital environment. This type of learning experience is particularly relevant in schools with limited laboratory facilities. The strong improvement observed in scientific competence may therefore reflect the combined contribution of STEM engineering design activities and virtual experimentation, which provide opportunities for students to evaluate evidence, solve problems, and conduct investigations. This interpretation is supported by Diego-Mantecón et al. [30], who found that project-based STEM instruction can strengthen inquiry-related competencies.

Among the science literacy dimensions measured in this study, scientific competence showed the highest N-Gain (0.78), followed by scientific knowledge (0.75), scientific attitude (0.68), and scientific context (0.67). The relatively higher gains in scientific competence and knowledge may be explained by the strong emphasis of the E-LKPD on inquiry, problem solving, evidence evaluation, and conceptual application. In contrast, scientific attitude and scientific context may require longer-term learning experiences and broader exposure to real-world scientific issues before substantial changes can be observed. This interpretation is consistent with previous studies that emphasize the role of contextual STEM learning in supporting scientific reasoning and literacy development [12], [13], [14], [30].

The findings also have implications for efforts to strengthen science literacy in Indonesia. Although this study was conducted at the elementary level, early development of scientific reasoning, inquiry skills, and evidence-based thinking is important for students' later science learning. Therefore, AI-integrated STEM-based learning materials may provide a promising instructional approach for

supporting foundational science literacy, particularly when they are designed to be pedagogically appropriate, contextually relevant, and responsive to students' learning needs [2], [5], [6].

Nevertheless, several limitations should be acknowledged. The study involved a relatively small sample from only two elementary schools, which limits the generalizability of the findings. In addition, the intervention was conducted within a limited period, and the study did not isolate the independent effects of the STEM and AI components. Future research should therefore involve larger and more diverse samples, longer intervention periods, and comparison groups using STEM-based E-LKPD without AI features in order to determine the specific contribution of AI integration.

4. CONCLUSION

This study developed an AI-integrated STEM-based E-LKPD for Grade V elementary science learning and evaluated its validity, practicality, and effectiveness in supporting students' science literacy. The developed product achieved high validity and practicality scores and produced a higher science literacy gain in the experimental group than in the control group. These findings indicate that the integration of STEM-oriented learning activities with adaptive quizzes, personalized feedback, and virtual science simulations has strong potential to support interactive and responsive science learning at the elementary level. The study also showed that the greatest improvements occurred in scientific competence and scientific knowledge, suggesting that the developed E-LKPD effectively supported inquiry, problem solving, evidence evaluation, and conceptual understanding. However, the findings should be interpreted within the limitations of the study, including the relatively small sample, limited research setting, and the absence of a STEM-only comparison group. Therefore, future research should involve larger and more diverse samples, longer intervention periods, and comparative designs that can examine the specific contribution of AI features within STEM-based learning environments.

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