



Enhancing Elementary Students' Scientific Literacy through AI-Powered Inquiry Learning: A Quasi-Experimental Study

Muhammad Nasheh Ulwan ✉, Universitas Pendidikan Indonesia, Indonesia

✉ ulwan@upi.edu

Abstract: Scientific literacy is an essential competency in elementary science education because students need to understand scientific phenomena, engage in inquiry, and interpret evidence to make reasoned decisions. However, conventional science instruction may provide limited opportunities for elementary students to engage in sustained inquiry and receive individualized learning support. This study investigated the effect of AI-powered inquiry learning on the scientific literacy of elementary school students. A quantitative approach with a quasi-experimental, non-equivalent pretest-posttest control group design was employed. The participants were 76 third-grade students at SD Negeri Anyar 1, Indonesia, comprising 38 students in the experimental class and 38 students in the control class. The experimental group participated in AI-powered inquiry learning, in which artificial intelligence was integrated into scientific questioning, investigation, evidence interpretation, feedback, and reflection, whereas the control group received conventional science instruction. Scientific literacy was measured using a researcher-developed assessment covering students' abilities to explain scientific phenomena, evaluate scientific inquiry, and interpret scientific evidence. Data were analyzed using descriptive statistics, Shapiro-Wilk normality testing, Levene's test, paired-samples t-tests, independent-samples t-tests, normalized gain analysis, and Cohen's *d*. The results showed that the experimental group improved from a pretest mean of 58.42 (*SD* = 8.17) to a posttest mean of 85.76 (*SD* = 6.21), whereas the control group increased from 57.89 (*SD* = 7.94) to 72.11 (*SD* = 7.28). The posttest difference between groups was statistically significant ($t = 8.79, p < .001$), with a large effect size (Cohen's $d = 2.03$). The normalized gain was also higher in the experimental group (0.66) than in the control group (0.34). These findings indicate that integrating AI-supported scaffolding into inquiry-based science instruction can substantially enhance elementary students' scientific literacy within the context examined.

Keywords: Artificial intelligence; inquiry learning; scientific literacy; elementary education; science education; quasi-experimental study.

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INTRODUCTION

Scientific literacy has become one of the most essential competencies required for learners in the twenty-first century. In an era characterized by rapid technological advancement,

information abundance, and increasingly complex societal challenges, students are expected not only to acquire scientific knowledge but also to apply scientific reasoning, evaluate evidence critically, and make informed decisions in everyday life. Consequently, scientific literacy has been widely recognized as a fundamental educational outcome that supports lifelong learning and responsible citizenship (OECD, 2019).

The importance of scientific literacy has been repeatedly emphasized in international educational frameworks. The Programme for International Student Assessment (PISA) defines scientific literacy as the ability to engage with science-related issues and ideas as reflective citizens through the explanation of phenomena, evaluation of scientific inquiry, and interpretation of evidence-based data (OECD, 2023). These competencies are increasingly relevant as societies confront environmental, health, and technological issues that require scientifically informed judgments.

Despite its recognized importance, scientific literacy remains a significant challenge in many educational systems worldwide. International assessments consistently reveal that many students struggle to connect scientific concepts with real-world contexts and often demonstrate limited ability to interpret evidence or formulate scientific explanations. Such challenges are particularly concerning at the elementary school level because foundational scientific understanding developed during childhood strongly influences subsequent academic achievement and attitudes toward science (Bybee, 2018).

In Indonesia, scientific literacy has emerged as a major educational concern over the past decade. Results from international assessments indicate that Indonesian students continue to perform below the OECD average in science-related competencies. Beyond assessment scores, studies have highlighted difficulties among elementary students in explaining scientific phenomena, designing investigations, and interpreting scientific evidence in authentic contexts. These findings suggest that improvements in science instruction are urgently needed to strengthen students' scientific literacy from an early age.

One factor contributing to the limited development of scientific literacy is the persistence of teacher-centered instructional approaches. Traditional science instruction often emphasizes memorization of facts and procedural knowledge rather than inquiry, exploration, and evidence-based reasoning. Although such approaches may support short-term knowledge acquisition, they frequently fail to cultivate deeper scientific understanding and transferable scientific thinking skills (National Research Council, 2018).

Contemporary educational research increasingly advocates inquiry-based learning as an effective pedagogical approach for addressing these limitations. Inquiry learning encourages students to formulate questions, investigate phenomena, collect evidence, analyze data, and construct explanations based on empirical findings. Through active engagement in scientific processes, students develop both conceptual understanding and higher-order thinking skills that are central to scientific literacy (Lazonder & Harmsen, 2016).

Inquiry learning aligns closely with constructivist theories of learning, which emphasize that knowledge is actively constructed through meaningful interactions with the environment. Within inquiry-oriented classrooms, students are positioned as active investigators rather than passive recipients of information. This shift promotes curiosity, engagement, and deeper understanding of scientific concepts while simultaneously strengthening scientific reasoning abilities.

Numerous studies have demonstrated the effectiveness of inquiry learning in improving scientific literacy outcomes. A systematic review conducted by Kustiarini and Azizah (2023) found that inquiry-based instruction consistently contributes to improvements in elementary students' scientific literacy across diverse learning contexts. The review further emphasized that inquiry activities supported by appropriate scaffolding and learning resources generate more meaningful learning experiences.

Similarly, recent meta-analytic evidence indicates that guided inquiry learning produces substantial positive effects on students' scientific literacy. Farhan et al. (2023) reported a large overall effect size for guided inquiry interventions across different educational levels, suggesting that inquiry-oriented learning environments significantly enhance learners' abilities to engage with scientific concepts and evidence.

Research conducted in elementary school settings has also revealed positive relationships between inquiry learning and the development of critical thinking skills, scientific reasoning, and science achievement. Inquiry-based activities encourage students to formulate hypotheses, evaluate alternative explanations, and justify conclusions using evidence, all of which represent essential dimensions of scientific literacy (Anggraini et al., 2020).

Although inquiry learning offers substantial pedagogical benefits, its implementation in elementary classrooms often encounters practical challenges. Many young learners require continuous guidance during investigative activities, while teachers frequently struggle to provide individualized support to students with diverse learning needs. Limited instructional time and large class sizes may further restrict opportunities for personalized inquiry experiences.

Recent advances in artificial intelligence (AI) offer promising opportunities to address these challenges. AI technologies have rapidly transformed educational practices by enabling adaptive learning, personalized feedback, intelligent tutoring, and automated assessment. UNESCO has emphasized the growing role of AI in supporting educational innovation and promoting learning environments that are more responsive to individual learner characteristics.

Within science education, AI has increasingly been integrated into learning environments to support inquiry processes. AI-powered systems can assist students in generating questions, identifying relevant information, organizing evidence, monitoring learning progress, and receiving immediate feedback. Such capabilities have the potential to strengthen students' engagement with scientific inquiry while reducing cognitive barriers that often hinder effective investigation.

The integration of AI into inquiry learning is particularly relevant for elementary education. Young learners frequently benefit from timely scaffolding that supports exploration without removing opportunities for independent thinking. AI-based learning tools can provide adaptive guidance tailored to individual learning trajectories, enabling students to engage more confidently in inquiry activities while maintaining appropriate levels of challenge and autonomy.

Emerging empirical evidence suggests that AI-supported inquiry environments can positively influence scientific learning outcomes. Recent studies have shown that AI-integrated inquiry modules enhance students' scientific literacy by facilitating personalized learning pathways, supporting evidence-based reasoning, and providing immediate instructional feedback. These features contribute to improved conceptual understanding and greater engagement in scientific learning activities.

Further evidence has demonstrated that AI-assisted inquiry approaches support students' understanding of scientific concepts and inquiry processes. For example, AI-powered mobile inquiry learning environments have been found to improve elementary students' scientific understanding, knowledge of scientific inquiry, and learning engagement. These findings indicate that AI can serve as an effective cognitive partner within inquiry-based science education.

Another promising area involves the use of AI-assisted educational assessment. Research has shown that AI-supported authentic assessment can enhance students' learning growth through continuous feedback and personalized monitoring of progress. Such capabilities are particularly valuable in inquiry learning contexts where formative assessment plays a crucial role in guiding students' scientific investigations.

Despite the growing body of literature on AI in education, empirical studies specifically examining the integration of AI-powered inquiry learning for improving

elementary students' scientific literacy remain relatively limited. Existing research has largely focused on technology-enhanced learning, STEM education, computational thinking, or general academic achievement, while comparatively few studies have investigated scientific literacy as a primary outcome variable in elementary science classrooms.

Furthermore, many previous studies have employed developmental, descriptive, or literature review approaches rather than rigorous experimental designs. Consequently, empirical evidence regarding the causal impact of AI-powered inquiry learning on elementary students' scientific literacy remains insufficient. Additional quasi-experimental studies are needed to establish whether AI-supported inquiry instruction generates measurable improvements compared with conventional learning approaches.

Another important research gap concerns the Indonesian elementary education context. Although inquiry learning and educational technology have been widely discussed, limited evidence is available regarding how AI-assisted inquiry environments function within authentic classroom settings involving young learners. Given the unique curricular and pedagogical characteristics of Indonesian elementary schools, localized empirical investigations are essential for informing future instructional practices.

This study addresses these gaps by examining the effect of AI-powered inquiry learning on the scientific literacy of elementary school students. Unlike previous studies that primarily investigated inquiry learning or AI separately, this research integrates both approaches into a unified instructional framework designed to promote active investigation, personalized support, and evidence-based reasoning. The integration of AI functions as adaptive scaffolding throughout the inquiry process, enabling students to engage more effectively in scientific exploration.

The novelty of this study lies in its focus on the combined influence of AI-powered learning technologies and inquiry-based pedagogy on scientific literacy among elementary students within an Indonesian context. By employing a quasi-experimental design involving experimental and control groups, the study provides empirical evidence regarding the effectiveness of this instructional approach. The findings are expected to contribute to the growing literature on AI-enhanced science education while offering practical implications for teachers, curriculum developers, and educational policymakers seeking innovative strategies to strengthen scientific literacy in elementary schools.

Accordingly, the purpose of this study is to investigate whether AI-powered inquiry learning significantly enhances elementary students' scientific literacy compared with conventional instruction. Through this investigation, the study seeks to provide evidence-based insights into the potential of AI-supported inquiry environments to foster scientific competencies that are increasingly essential for learners in the digital age.

METHODS

This study employed a quantitative approach using a quasi-experimental research design with a non-equivalent pretest-posttest control group structure. The selection of a quasi-experimental design was considered appropriate because the study was conducted within an authentic school setting where existing classroom groups could not be randomly reassigned. Such a design enables researchers to investigate causal relationships between instructional interventions and learning outcomes while preserving the ecological validity of the educational environment. The design has been widely utilized in contemporary educational research examining the effectiveness of innovative instructional approaches, particularly those involving inquiry-based learning and technology-enhanced pedagogies. The study was conducted during the second semester of the 2025/2026 academic year at SD Negeri Anyar 1, Indonesia. The school was selected because it had implemented the national curriculum consistently and possessed adequate digital infrastructure to support the integration of artificial intelligence within classroom instruction. Furthermore, preliminary observations revealed that science instruction was predominantly teacher-

centered and focused primarily on content transmission, providing an appropriate context for investigating the effectiveness of AI-powered inquiry learning in fostering scientific literacy.

The research involved all third-grade students enrolled at SD Negeri Anyar 1. Two intact classes participated in the study. Grade III-a, consisting of 38 students, served as the experimental group and received instruction through the AI-powered inquiry learning model. Grade III-b, consisting of 38 students, served as the control group and received conventional science instruction. Consequently, the total sample comprised 76 students. Because both classes possessed relatively similar demographic characteristics, educational backgrounds, and previous science achievement levels, they were considered sufficiently comparable for quasi-experimental analysis.

Prior to the implementation of the intervention, ethical approval was obtained from the school administration, and informed consent was secured from parents or guardians. Participation in the study was voluntary, and students were informed that all collected data would be used exclusively for research purposes. Confidentiality was maintained throughout the study by assigning identification codes to participants rather than recording personal information.

The independent variable investigated in this study was AI-powered inquiry learning, while the dependent variable was scientific literacy. AI-powered inquiry learning was conceptualized as an instructional model integrating the fundamental phases of inquiry learning with artificial intelligence-based learning support systems. Within this framework, students engaged in scientific investigations while receiving adaptive guidance, personalized feedback, and AI-assisted scaffolding designed to facilitate questioning, evidence collection, data interpretation, and scientific explanation. This conceptualization aligns with recent developments in AI-enhanced inquiry learning environments that emphasize learner agency while simultaneously providing individualized instructional support.

The instructional intervention was implemented over eight consecutive weeks, with two science lessons conducted each week. Each lesson lasted approximately 80 minutes. Consequently, the intervention consisted of sixteen instructional sessions. Both experimental and control groups studied identical science content, learning objectives, and assessment materials. The primary difference between the two groups concerned the instructional approach employed during classroom learning.

In the experimental group, learning activities were organized according to an AI-powered inquiry learning framework. During the orientation phase, students were introduced to authentic scientific phenomena through contextual problems relevant to their daily experiences. Artificial intelligence tools were subsequently utilized to stimulate curiosity, generate exploratory questions, and provide multimedia representations of scientific concepts. The AI system functioned as a cognitive scaffold rather than a source of direct answers, encouraging students to formulate hypotheses and identify variables relevant to the investigated phenomena.

During the investigation phase, students worked collaboratively to gather information, conduct simple experiments, and document observational evidence. AI-supported learning applications provided real-time prompts, procedural guidance, and adaptive feedback based on students' responses. These features enabled students to receive individualized support while maintaining active engagement in the inquiry process. Consistent with recent studies, the AI component functioned as an inquiry facilitator designed to strengthen evidence-based reasoning rather than replace scientific thinking.

During the analysis phase, students interpreted collected data, compared findings with initial hypotheses, and constructed scientific explanations. AI-generated feedback assisted students in identifying inconsistencies, recognizing patterns, and refining scientific arguments. The technology encouraged reflective thinking by prompting

students to justify conclusions using empirical evidence rather than intuition or memorization.

The final phase focused on communication and reflection. Students presented findings, defended interpretations, and engaged in classroom discussions regarding scientific explanations. Artificial intelligence tools facilitated reflective evaluation by generating personalized learning summaries and identifying areas requiring further conceptual development. Through these processes, students experienced scientific inquiry as an iterative cycle of questioning, investigation, evidence evaluation, and explanation construction.

Conversely, students in the control group received conventional instruction commonly practiced within the school context. Learning activities primarily consisted of teacher explanations, textbook reading, question-and-answer sessions, and completion of structured exercises. Although students participated in classroom discussions, opportunities for independent inquiry and personalized learning support were substantially more limited than those provided within the experimental condition. Scientific literacy served as the primary outcome variable and was measured using a researcher-developed Scientific Literacy Test grounded in the scientific literacy framework proposed by the Organisation for Economic Co-operation and Development (OECD). The instrument was designed to assess students' ability to explain scientific phenomena, evaluate scientific investigations, interpret scientific evidence, and apply scientific knowledge to real-world situations. These dimensions have been consistently recognized as core components of scientific literacy in contemporary science education research.

The Scientific Literacy Test consisted of twenty-four items comprising eighteen multiple-choice questions and six open-ended items. Multiple-choice items measured conceptual understanding and scientific reasoning, while open-ended items assessed students' ability to formulate explanations, interpret evidence, and justify conclusions. The integration of both item formats was intended to provide a comprehensive assessment of scientific literacy competencies and reduce potential measurement bias associated with reliance on a single assessment format.

Prior to implementation, the instrument underwent rigorous validation procedures involving three experts in science education, educational assessment, and elementary curriculum studies. Expert reviewers evaluated content relevance, construct alignment, linguistic clarity, and age appropriateness. Revisions were subsequently made based on expert recommendations to ensure content validity and instructional suitability for third-grade learners.

A pilot study involving 32 elementary students from a neighboring school was conducted to evaluate psychometric quality. Item analysis indicated that all retained items possessed acceptable discrimination and difficulty indices. Reliability analysis using Cronbach's alpha yielded a coefficient of .89, indicating high internal consistency. These findings suggest that the instrument was sufficiently reliable for measuring elementary students' scientific literacy.

In addition to the scientific literacy test, classroom observations were conducted throughout the intervention period to ensure treatment fidelity. Observation protocols focused on student participation, inquiry engagement, utilization of AI tools, collaborative interactions, and adherence to instructional procedures. Observational data were not used as primary outcome measures but served to verify consistent implementation of the intervention. Table 1 presents the operational definition of variables and indicators used in this study.

Table 1. Operational Definitions of Research Variables

Variable	Dimension	Indicator
AI-Powered Inquiry Learning	Inquiry Orientation	Question generation, hypothesis formulation, investigation planning

AI-Powered Inquiry Learning	AI Scaffolding	Personalized feedback, adaptive guidance, reflective prompts
AI-Powered Inquiry Learning	Evidence-Based Reasoning	Data collection, analysis, interpretation, scientific explanation
Scientific Literacy	Explaining Scientific Phenomena	Understanding concepts and applying scientific knowledge
Scientific Literacy	Evaluating Scientific Inquiry	Assessing procedures and scientific investigations
Scientific Literacy	Interpreting Scientific Evidence	Analyzing data and drawing evidence-based conclusions

Data collection occurred in three stages. The first stage involved administering the pretest before the intervention to determine students' initial scientific literacy levels. The second stage involved implementation of the instructional treatment over the eight-week intervention period. The final stage involved administering the posttest immediately following completion of the intervention. Both groups completed identical pretest and posttest instruments under standardized testing conditions.

Data analysis was conducted using IBM SPSS Statistics version 27. Descriptive statistics were initially generated to examine mean scores, standard deviations, minimum scores, maximum scores, and score distributions. These analyses provided an overview of students' scientific literacy performance before and after the intervention.

Inferential statistical procedures were subsequently employed to evaluate the effectiveness of the intervention. Assumptions of normality and homogeneity were examined prior to hypothesis testing. Normality was assessed using the Shapiro-Wilk test, whereas homogeneity of variance was evaluated through Levene's test. The results indicated that the data met the assumptions required for parametric analysis.

To examine within-group improvement, paired-samples t-tests were conducted separately for the experimental and control groups. These analyses determined whether statistically significant changes occurred between pretest and posttest scores within each instructional condition. To investigate differences between groups following the intervention, independent-samples t-tests were performed using posttest scores. Additional analyses of normalized gain scores were conducted to evaluate the magnitude of learning improvement attributable to the intervention.

Effect size calculations were incorporated to determine the practical significance of observed differences. Cohen's *d* values were interpreted according to established educational research guidelines, thereby enabling a more comprehensive understanding of the instructional impact beyond statistical significance alone. Reporting both statistical significance and effect size is increasingly recommended within contemporary educational research because it provides stronger evidence regarding educational effectiveness and practical relevance.

Through this methodological framework, the study sought to generate robust empirical evidence regarding the effectiveness of AI-powered inquiry learning in enhancing elementary students' scientific literacy. The combination of a quasi-experimental design, validated measurement instruments, systematic intervention procedures, and rigorous statistical analyses was intended to ensure methodological rigor, reliability, and reproducibility of the research findings.

RESULTS

The present study investigated the effectiveness of AI-powered inquiry learning in enhancing elementary students' scientific literacy. Prior to hypothesis testing, descriptive and inferential statistical analyses were conducted to examine the distribution of data, determine baseline equivalence between groups, and evaluate the impact of the

intervention on students' scientific literacy outcomes. Table 2 presents the descriptive statistics of scientific literacy scores in both groups before and after the intervention.

Table 2. Descriptive Statistics of Scientific Literacy Scores

Group	Test	N	Mean	SD	Minimum	Maximum
Experimental	Pretest	38	58.42	8.17	42	74
Experimental	Posttest	38	85.76	6.21	71	97
Control	Pretest	38	57.89	7.94	43	73
Control	Posttest	38	72.11	7.28	58	88

The descriptive statistics indicate that both groups exhibited relatively similar scientific literacy levels before the intervention. The mean pretest score of the experimental group was 58.42, while the control group obtained a mean score of 57.89. Following the intervention, substantial improvement was observed in both groups; however, the increase was considerably greater in the experimental group. The posttest mean score of the experimental group reached 85.76, whereas the control group achieved a mean score of 72.11. Before conducting parametric analyses, assumption testing was performed. The results of the normality test are presented in Table 3.

Table 3. Results of the Shapiro–Wilk Normality Test

Group	Test	Statistic	Sig.
Experimental	Pretest	.972	.417
Experimental	Posttest	.968	.322
Control	Pretest	.976	.528
Control	Posttest	.971	.391

The Shapiro–Wilk significance values for all datasets exceeded .05, indicating that the data were normally distributed. Therefore, parametric statistical procedures could be applied. Homogeneity testing was subsequently conducted using Levene's Test, and the results are displayed in Table 4.

Table 4. Results of Homogeneity Testing

Variable	Levene Statistic	Sig.
Pretest Scores	0.184	.669
Posttest Scores	1.237	.270

The significance values obtained from Levene's Test were greater than .05, indicating that the variances of the two groups were homogeneous. To determine the effectiveness of the intervention within each group, paired-samples t-tests were conducted. The results are presented in Table 5.

Table 5. Results of Paired-Samples t-Test

Group	Mean Difference	t	Sig.
Experimental	27.34	19.82	.000
Control	14.22	10.74	.000

The paired-samples t-test results revealed statistically significant improvements in scientific literacy within both groups. However, the magnitude of improvement was substantially larger in the experimental group, which gained an average of 27.34 points compared to 14.22 points in the control group. To examine post-intervention differences

between groups, an independent-samples t-test was performed. The results are shown in Table 6.

Table 6. Results of Independent-Samples t-Test on Posttest Scores

Group	Mean	SD	t	Sig.
Experimental	85.76	6.21	8.79	.000
Control	72.11	7.28		

The analysis revealed a statistically significant difference between the experimental and control groups after the intervention. Students who participated in AI-powered inquiry learning achieved significantly higher scientific literacy scores than students who experienced conventional instruction. To determine the magnitude of learning improvement, normalized gain analysis was conducted. The results are presented in Table 7.

Table 7. N-Gain Analysis

Group	N-Gain	Category
Experimental	0.66	Medium-High
Control	0.34	Medium

The experimental group demonstrated a substantially higher N-Gain score than the control group, indicating more effective learning progress throughout the intervention period. To evaluate practical significance, effect size analysis was performed using Cohen's d.

Table 8. Effect Size Analysis

Comparison	Cohen's d	Interpretation
Experimental vs Control Posttest	2.03	Very Large

The effect size value of 2.03 indicates that AI-powered inquiry learning exerted a very large educational impact on elementary students' scientific literacy.

DISCUSSION

The findings of this study demonstrate that AI-powered inquiry learning significantly improved elementary students' scientific literacy. Students exposed to AI-supported inquiry instruction achieved substantially higher posttest scores than those receiving conventional instruction. The large effect size further suggests that the observed differences were not only statistically significant but also educationally meaningful. These findings provide strong evidence that integrating artificial intelligence into inquiry-oriented science instruction can enhance students' capacity to understand, investigate, and explain scientific phenomena.

One notable finding concerns the substantial increase in scientific literacy scores observed in the experimental group. The average gain of more than 27 points indicates that students experienced meaningful conceptual and procedural development throughout the intervention period. Such improvement suggests that AI-assisted inquiry environments successfully supported students in constructing scientific understanding through active engagement rather than passive knowledge reception.

The superiority of the AI-powered inquiry approach may be explained through constructivist learning theory. According to constructivist perspectives, learners develop understanding through active interaction with experiences, ideas, and evidence. Inquiry learning naturally embodies these principles because students investigate questions, generate explanations, and evaluate evidence independently. The incorporation of AI

further strengthened these processes by providing adaptive scaffolding tailored to individual learning needs.

The present findings are consistent with previous studies indicating that inquiry-based learning positively influences scientific literacy development. Research conducted by Lazonder and Harmsen (2016) demonstrated that inquiry learning enhances students' scientific reasoning and conceptual understanding when supported by appropriate guidance. The current study extends these findings by demonstrating that artificial intelligence can serve as an effective mechanism for delivering such guidance within elementary science classrooms.

Another important finding concerns the role of personalized feedback in promoting scientific literacy. Students in the experimental group received immediate AI-generated feedback during inquiry activities. Such feedback enabled learners to identify misconceptions, refine hypotheses, and strengthen evidence-based explanations. Educational research has consistently demonstrated that timely feedback represents one of the most powerful influences on student achievement (Hattie, 2023).

The results also support UNESCO's recent position regarding the transformative potential of artificial intelligence in education. UNESCO (2024) emphasizes that AI can facilitate personalized learning experiences that accommodate individual differences among learners. In the present study, AI-supported scaffolding appeared to help students navigate inquiry tasks more effectively while maintaining active ownership of the learning process.

Scientific literacy requires more than memorization of scientific facts; it demands the ability to apply knowledge within meaningful contexts. The inquiry activities implemented in this study required students to investigate authentic phenomena, interpret observational data, and justify conclusions using evidence. Such experiences likely contributed to the substantial gains observed among students in the experimental group. These findings align closely with OECD (2023), which identifies evidence-based reasoning as a core component of scientific literacy.

The findings additionally reveal that AI-supported inquiry learning promoted deeper engagement with scientific investigation. Throughout the intervention, students actively participated in questioning, experimenting, discussing, and reflecting. Increased engagement likely contributed to improved learning outcomes because students were more frequently involved in cognitively demanding activities than those in the conventional classroom setting.

The relatively lower gains observed in the control group deserve consideration. Although conventional instruction produced significant improvement, the magnitude of change was considerably smaller. This outcome suggests that traditional teacher-centered approaches remain capable of supporting learning but may be less effective in developing higher-order competencies associated with scientific literacy.

An important contribution of this study lies in its focus on elementary school learners. Much of the existing literature concerning AI in education has concentrated on secondary or higher education contexts. Consequently, empirical evidence regarding younger learners remains comparatively limited. The present findings indicate that elementary students are capable of benefiting substantially from AI-supported inquiry experiences when instructional design is developmentally appropriate.

The results further suggest that artificial intelligence should not be viewed as a replacement for teachers. Instead, AI functioned as an instructional partner that complemented teacher facilitation. Teachers continued to guide discussions, monitor learning activities, and support classroom interactions, while AI provided personalized scaffolding that would be difficult to deliver consistently to all students in a large classroom. This finding corresponds with recent perspectives emphasizing human-centered AI integration in education (Holmes et al., 2022).

The large effect size identified in this study is particularly noteworthy. Educational interventions frequently produce statistically significant results with modest practical

impacts. In contrast, the effect size observed here indicates a substantial educational advantage associated with AI-powered inquiry learning. This suggests that the intervention generated meaningful changes in students' scientific literacy competencies rather than merely producing minor score increases.

The findings may also be interpreted through the lens of cognitive load theory. Inquiry learning can sometimes impose substantial cognitive demands on novice learners. Without adequate support, students may struggle to organize information, formulate explanations, or interpret evidence effectively. The AI-based scaffolding implemented in this study likely reduced unnecessary cognitive burden while preserving productive cognitive engagement, thereby facilitating more efficient learning processes.

Another explanation relates to metacognitive development. The AI system regularly prompted students to reflect on their reasoning, evaluate evidence, and reconsider conclusions. Such reflective activities encourage metacognitive awareness, which has been identified as a critical factor influencing scientific literacy and academic achievement. Students who monitor and regulate their thinking are generally better equipped to engage in scientific inquiry and evidence-based decision making.

The study also contributes to the growing literature concerning technology-enhanced science education in developing countries. While many investigations of AI-assisted learning originate from technologically advanced educational systems, evidence from Indonesian elementary schools remains scarce. The present findings therefore provide valuable empirical support for the feasibility and effectiveness of AI-supported instructional innovation within local educational contexts.

From a practical perspective, the results suggest that schools seeking to strengthen scientific literacy should consider integrating AI technologies within inquiry-oriented instructional frameworks. The effectiveness observed in this study indicates that educational technology yields the greatest benefits when embedded within sound pedagogical practices rather than implemented as an isolated innovation.

Nevertheless, several limitations should be acknowledged. The study was conducted within a single elementary school and involved a relatively limited sample size. Consequently, caution should be exercised when generalizing findings to broader populations. Future studies should involve larger and more diverse samples across multiple educational settings.

Future research may also explore additional outcome variables such as scientific reasoning, critical thinking, problem-solving skills, creativity, and learning motivation. Investigations examining long-term retention effects and variations in AI-supported inquiry models would further enrich understanding of how artificial intelligence can contribute to science education.

Overall, the findings provide compelling evidence that AI-powered inquiry learning represents a promising instructional approach for enhancing elementary students' scientific literacy. By combining the strengths of inquiry-based pedagogy with adaptive technological support, the intervention successfully fostered scientific understanding, evidence-based reasoning, and meaningful engagement in science learning. These outcomes reinforce the growing view that thoughtfully designed AI-enhanced learning environments can play an important role in preparing young learners for the scientific and technological demands of the twenty-first century.

CONCLUSION

This study examined the effect of AI-powered inquiry learning on elementary students' scientific literacy through a quasi-experimental design involving third-grade students at SD Negeri Anyar 1. The findings revealed that students who participated in AI-powered inquiry learning achieved significantly higher scientific literacy scores than those who received conventional instruction. The experimental group demonstrated greater improvement in scientific literacy, as reflected in higher posttest scores, stronger

normalized gain values, and a large effect size. These results indicate that the integration of artificial intelligence within inquiry-based learning can provide effective instructional support for developing students' abilities to explain scientific phenomena, evaluate scientific investigations, and interpret scientific evidence.

The effectiveness of the intervention appears to be associated with the combination of inquiry-oriented learning activities and AI-assisted scaffolding, which enabled students to engage actively in scientific exploration while receiving personalized guidance and feedback throughout the learning process. The findings suggest that AI-powered inquiry learning represents a promising pedagogical approach for supporting scientific literacy development in elementary science education. Nevertheless, the results should be interpreted within the context of the study's scope, which was limited to a single school and a specific grade level. Future research involving broader educational settings, larger samples, and longer intervention periods is needed to further examine the applicability and sustainability of AI-supported inquiry learning across diverse learning contexts.

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