



The Influence of the Artificial Intelligence Integrated Project-Based Learning Model on Ability Critical Thinking of Elementary School Students

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ABSTRACT

Critical thinking is a crucial 21st-century competency that needs to be cultivated starting at the elementary school level. However, instruction that remains focused on information delivery has not yet fully provided students with opportunities to analyze problems, evaluate information, draw conclusions, and provide evidence-based explanations. This study aims to analyze the impact of an Artificial Intelligence (AI)-integrated Project-Based Learning (PjBL) model on the critical thinking skills of elementary school students, describe the improvement in these skills before and after instruction, and measure the model's effectiveness using the N-gain score. The study employed a quantitative approach using a quasi-experimental method and a pretest-posttest control group design. The subjects consisted of 60 fifth-grade elementary school students divided into an experimental group and a control group, with 30 students in each. The experimental group received AI-integrated PjBL instruction over eight sessions, while the control group received conventional instruction. Data were collected using an essay test assessing critical thinking skills, covering indicators such as interpretation, analysis, evaluation, inference, and explanation. Data analysis involved descriptive statistics, N-gain calculation, normality and homogeneity tests, and an independent-samples t-test. The results showed that the experimental group's average critical thinking score rose from 48.33 to 79.17 (N-gain = 0.68), whereas the control group's score rose from 47.67 to 61.50 (N-gain = 0.33). The t-test results indicated a significant difference between the two groups ($t = 8.74$; $p < 0.001$). Thus, AI-integrated PjBL is more effective than conventional instruction in enhancing the critical thinking skills of elementary school students. Integrating AI supported by teacher guidance and information verification activities has the potential to strengthen students' processes of analysis, evaluation, problem-solving, and reflection.

Keywords: Artificial Intelligence; Project-Based Learning; critical thinking; IPAS (Natural and Social Sciences); elementary school.



INTRODUCTION

The rapid development of digital technology and artificial intelligence (AI) has transformed the educational landscape and increasingly influenced how students access information, solve problems, collaborate, and construct knowledge. In the context of 21st-century education, schools are expected not only to facilitate the acquisition of subject knowledge but also to develop higher-order cognitive competencies, particularly critical thinking, problem solving, creativity, communication, and collaboration. Critical thinking is particularly important because students are required to examine information from multiple sources, evaluate the credibility of evidence, identify relationships among ideas, formulate reasoned judgments, and make decisions based on evidence rather than simply accepting information. This need has become increasingly important in the digital era, in which students are exposed to large amounts of information and increasingly sophisticated AI-generated content.

The development of these competencies remains a challenge in elementary education. International assessment data indicate that Indonesian students continue to experience difficulties in reading, reasoning, and applying knowledge to unfamiliar contexts. The PISA 2022 results, for example, show that Indonesian students' performance in reading, mathematics, and science remains below the OECD average, indicating the need for learning approaches that provide greater opportunities for reasoning, problem solving, and application of knowledge in authentic situations (OECD, 2023). At the elementary school level, this challenge is particularly important because the development of higher-order thinking needs to be initiated from an early stage through learning experiences that actively involve students in investigating problems, constructing explanations, evaluating evidence, and producing solutions.

One pedagogical approach that is relevant to this need is Project-Based Learning (PjBL). PjBL places students in meaningful learning situations in which they investigate authentic problems, plan and implement projects, collaborate with peers, evaluate information, and communicate the products or solutions they develop. These characteristics provide opportunities for students to practice higher-order cognitive processes rather than merely memorize information. Evidence from a meta-analysis of 29 studies demonstrates that PjBL has a positive effect on students' critical thinking skills and is generally more effective than traditional instructional approaches, although its effectiveness can vary according to educational level and the characteristics of the comparison model (Tafakur et al., 2023). Thus, PjBL provides a strong pedagogical foundation for developing critical thinking because students are continuously required to interpret problems, analyze information, evaluate alternatives, and formulate evidence-based solutions.

Nevertheless, the implementation of PjBL in elementary schools is not without challenges. Project activities require students to search for relevant information, interpret data, receive feedback, revise their work, and manage complex learning processes. In conventional classroom settings, teachers may experience difficulties in providing individualized feedback to every student throughout the project process. Students may also have different levels of prior knowledge, learning pace, and ability to access and process information. Consequently, PjBL requires appropriate technological and pedagogical support so that project activities do not merely result in the production of a final product but genuinely facilitate the development of higher-order thinking skills.

The rapid advancement of Artificial Intelligence offers a potential solution to some of these challenges. AI-based educational technologies can provide students with immediate

feedback, facilitate access to learning resources, support personalized learning, and assist teachers in designing learning activities and assessment. Recent systematic and meta-analytic evidence indicates that AI and computational technologies can positively influence student learning outcomes, although the effectiveness of such technologies depends substantially on how they are pedagogically integrated into learning processes (García-Martínez et al., 2023). Similarly, recent reviews of generative AI in K–12 education demonstrate that AI is increasingly being incorporated into teaching and learning processes, but its educational value depends on purposeful instructional design, teacher guidance, and responsible use rather than on technology alone (Marzano, 2025).

Importantly, AI should not be positioned merely as a tool for obtaining answers. Its educational value is greater when students are encouraged to interrogate, compare, verify, and critically evaluate AI-generated information. Recent research on generative AI and critical thinking indicates that AI can facilitate analytical thinking, argument construction, information synthesis, and independent exploration; however, excessive dependence on AI may conversely reduce learners' cognitive engagement and analytical autonomy (Liu et al., 2025). Therefore, the integration of AI into learning should be accompanied by activities that require students to question AI outputs, identify inaccuracies, compare AI-generated information with other sources, and justify their conclusions. Such an approach is particularly compatible with PjBL because project-based activities naturally require students to use information as evidence for making decisions and producing authentic solutions.

The combination of PjBL and AI therefore offers a potentially complementary learning framework. PjBL provides the pedagogical structure through authentic problems, collaborative inquiry, project planning, implementation, evaluation, and product creation, while AI can function as a cognitive and technological support mechanism by providing information resources, personalized feedback, scaffolding, and opportunities for iterative exploration. The integration of these two components can potentially create a learning environment in which students are not passive recipients of AI-generated information but active evaluators and users of information. In this context, technology integration is expected to strengthen rather than replace students' critical cognitive processes.

Recent empirical evidence also supports the relevance of integrating AI with project-based learning at the elementary level. A quasi-experimental study involving elementary school students reported that AI-based PjBL produced differences in critical thinking outcomes compared with non-AI-based PjBL, indicating the potential of AI-supported project learning for strengthening students' higher-order thinking (Ramadhani & Sari, 2026). In addition, recent studies of PjBL in elementary education have continued to demonstrate its potential for improving critical thinking, particularly when project activities are connected with contextual problems and supported by technology. These findings strengthen the argument that the effectiveness of PjBL may be enhanced when digital technologies are intentionally incorporated into the learning process rather than used merely as supplementary media.

Despite these developments, an important research gap remains. Existing studies have separately examined the effectiveness of PjBL for developing critical thinking and the potential contribution of AI to learning. However, empirical research examining the integrated implementation of AI within the complete PjBL learning process for developing critical thinking among elementary school students in the Indonesian context remains limited. Moreover, previous studies have not sufficiently explained how AI can be integrated into each stage of PjBL while maintaining students' active cognitive involvement. This gap is particularly important because the use of AI without appropriate pedagogical scaffolding may encourage students to accept AI-generated answers uncritically, whereas properly structured integration may instead provide opportunities for evaluation, verification, argumentation, and problem solving.

The present study addresses this gap by investigating the influence of an Artificial Intelligence-integrated Project-Based Learning model on elementary school students' critical thinking abilities. The novelty of this study lies in the integration of AI into the PjBL learning cycle, in which AI is utilized not simply as a source of information but as a learning support mechanism for project planning, information exploration, feedback, evaluation, and revision. Students are positioned as active users and evaluators of AI-generated information so that interaction with AI becomes part of the critical-thinking learning process. This approach is expected to provide empirical evidence concerning whether the combination of authentic project-based learning and structured AI support can produce greater improvements in students' critical thinking than conventional learning.

Based on the theoretical and empirical considerations above, this study aims to: (1) describe the critical thinking ability of elementary school students before and after the implementation of the AI-integrated PjBL model; (2) analyze differences in critical thinking ability between students who receive AI-integrated PjBL and those who receive conventional learning; and (3) determine the effectiveness of the AI-integrated PjBL model based on students' learning gains. The findings are expected to contribute both theoretically and practically to the development of technology-enhanced learning models for strengthening critical thinking in elementary education.

RESEARCH METHODS

Research Design

This study employed a quantitative approach using a quasi-experimental method with a pretest-posttest control group design. The design was selected because individual random assignment was not feasible within the existing classroom structure. Quasi-experimental designs with pretest and posttest measurements are appropriate for evaluating educational interventions when intact classroom groups must be maintained and a comparison group is available. Recent systematic reviews of project-based learning research have also identified pretest-posttest and independent-group designs as appropriate approaches for examining changes in students' critical thinking following instructional interventions (Loyens et al., 2023). Two intact fifth-grade classes were involved in the study. One class was designated as the experimental group and received the Artificial Intelligence-integrated Project-Based Learning (AI-integrated PjBL) intervention, whereas the other class served as the control group and received conventional learning. The research design is presented as follows:

Group	Pretest	Treatment	Posttest
Experimental	O ₁	X ₁	O ₂
Control	O ₃	X ₂	O ₄

Description:

O₁ and O₃ represent the pretest scores of the experimental and control groups, respectively;
O₂ and O₄ represent the corresponding posttest scores;
X₁ represents the AI-integrated PjBL intervention; and
X₂ represents conventional instruction.

The use of a control group was intended to strengthen the interpretation of the intervention effect by allowing changes in the experimental group to be compared with changes occurring under conventional instruction. This is particularly relevant in PjBL research because previous systematic evidence has identified the absence of appropriate comparison groups as

one of the methodological weaknesses that can reduce the strength of causal interpretations in studies of project-based learning (Loyens et al., 2023).

Participants and Sampling

The population consisted of all fifth-grade students enrolled in public elementary schools in Bandung City during the 2024/2025 academic year. The sample consisted of 60 students from two intact classes, with 30 students assigned to the experimental group and 30 students assigned to the control group. The sample size and group composition were retained from the original research data.

Participants were selected using purposive sampling. The selection criteria included: (1) the school had adequate internet connectivity to support AI-assisted learning activities; (2) teachers had basic competence in using digital learning technologies; and (3) digital devices were available for students during the intervention. These criteria were established to ensure that the technological conditions required for AI-supported learning were available throughout the intervention.

Research Variables

The independent variable was the Artificial Intelligence-integrated Project-Based Learning model, while the dependent variable was students' critical thinking ability.

The AI-integrated PjBL model was operationally defined as project-based learning in which AI tools were deliberately incorporated into selected stages of the project cycle to support problem formulation, project planning, information exploration, feedback, evaluation, and reflection. AI was positioned as a learning support mechanism rather than as a replacement for students' reasoning. The AI tools used in the experimental group included Quizizz AI and GPT-based chatbot. These tools were used to support question generation, project planning, formative feedback, rubric development, information exploration, and reflection. Students were instructed to treat AI-generated information as material for examination rather than as an automatically correct answer.

Critical Thinking Instrument

Students' critical thinking skills were measured using an essay test administered before and after the intervention. The instrument consisted of five open-ended questions designed to assess students' abilities to interpret information, analyze evidence, consider alternatives, formulate inferences, and explain conclusions regarding the Natural and Social Sciences (IPAS) topic of ecosystems and environmental balance. The critical thinking indicators assessed were:

1. interpretation;
2. analysis;
3. evaluation;
4. inference; and
5. explanation.

The use of open-ended tasks was intended to capture students' reasoning processes rather than merely their ability to select correct answers. This approach is consistent with recent research indicating that critical thinking in PjBL environments involves processes such as analyzing problems, evaluating evidence, making inferences, and explaining conclusions (Loyens et al., 2023). Meta-analytic evidence also indicates that PjBL has a positive effect on critical thinking, although the magnitude of its effect can depend on the educational level and comparison condition (Tafakur et al., 2023).

Each response was evaluated using an analytical scoring rubric. The scoring procedure considered both the correctness of the response and the quality of the reasoning demonstrated by the students.

Instrument Validity and Reliability

Before administration, the critical thinking instrument was reviewed by three experts with expertise in elementary education, educational assessment, and critical thinking. The expert review examined the alignment between the test items, learning objectives, critical thinking indicators, content, language, and developmental characteristics of fifth-grade students.

The instrument was subsequently tested on students with characteristics similar to, but independent from, the research sample. Reliability analysis was conducted using Cronbach's Alpha. The resulting coefficient was $\alpha = 0.84$, indicating high internal consistency. These instrument validation and reliability procedures were reported in the original study.

For the final manuscript, it is recommended that the authors report the numerical results of expert validation, such as **Aiken's V or Content Validity Index (CVI)**, if these calculations were performed. Reporting item-level validity evidence would improve methodological transparency and make the instrument development process more reproducible. This recommendation is particularly relevant because recent reviews of AI-related educational research have emphasized the importance of transparent measurement and research-design reporting when evaluating technology-supported learning interventions (Wang et al., 2024).

Data Analysis

Data analysis consisted of descriptive and inferential statistical procedures. Descriptive statistics included the mean, standard deviation, minimum score, maximum score, and normalized gain (N-gain). The assumptions of normality and homogeneity were examined before hypothesis testing. The Shapiro-Wilk test was used to assess the normality of the data, while Levene's test was used to examine homogeneity of variance between groups.

After the assumptions were satisfied, an independent-samples t-test was conducted at a significance level of $\alpha = 0.05$ to determine whether a statistically significant difference existed between the critical thinking scores of the experimental and control groups. The original study reported that the posttest data met the normality and homogeneity assumptions, with Levene's test producing $F = 0.89$ and $p = 0.35$, after which the independent-samples t-test was conducted. To measure the magnitude of students' improvement, N-gain was calculated using the following formula:

$$\text{N-gain} = (\text{Posttest} - \text{Pretest}) / (\text{Maximum Score} - \text{Pretest})$$

The N-gain results were interpreted according to conventional categories of improvement.

RESULTS AND DISCUSSION

Results

1. Students' Critical Thinking Skills Before and After the Intervention

The primary aim of this study was to describe students' critical thinking skills before and after the implementation of an Artificial Intelligence (AI)-integrated Project-Based Learning (PjBL) model. Critical thinking skills were measured using essay tests administered before (pretest) and after (posttest) the intervention. The study involved 60 fifth-grade elementary school students, comprising 30 students in the experimental group and 30 students in the control group. The results of the descriptive analysis regarding the critical thinking skills of both groups are presented in Table 1.

Table 1. Comparison of Critical Thinking Skills between the Experimental and Control Groups

Group	N	Average Pre test	Average Post test	N gain	Category
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Experimental	30	48,33	79,17	0,68	Medium-high
Control	30	47,67	61,50	0,33	Medium

Source: Research data

Based on Table 1, the initial critical thinking abilities of both groups were relatively similar. The experimental group's average pretest score was 48.33, while the control group's was 47.67. The difference in initial averages between the two groups was only 0.66 points; thus, descriptively, the groups were relatively comparable prior to the intervention. Following the intervention, an improvement in critical thinking ability was observed in both groups. However, the improvement in the experimental group was greater than that in the control group. The experimental group's average posttest score rose to 79.17—an increase of 30.84 points from the pretest—whereas the control group's average posttest score rose to 61.50, an increase of 13.83 points.

Thus, in descriptive terms, the increase in the experimental group's average critical thinking skills was more than double that of the control group. These results indicate a tendency for AI-integrated PjBL to yield a greater improvement in critical thinking skills compared to conventional instruction. This improvement is also reflected in the N-gain scores: the experimental group achieved an N-gain of 0.68, whereas the control group achieved 0.33. These values indicate that the improvement in the experimental group's critical thinking skills fell within the medium-to-high category, while the control group fell within the medium category.

2. Differences in Critical Thinking Skills between Experimental and Control Groups

The second research objective was to analyze the difference in critical thinking skills between students receiving instruction via AI-integrated PjBL and those receiving conventional instruction. Prior to hypothesis testing, the posttest data were examined to ensure that the assumptions for parametric statistical analysis were met. Normality was assessed using the Shapiro-Wilk test, while homogeneity was assessed using Levene's test.

The Shapiro-Wilk test results indicated that the posttest data for both groups were normally distributed, with a significance value of $p > 0.05$. Furthermore, the homogeneity test yielded an F-value of 0.89 with $p = 0.35$. Since $p > 0.05$, it can be concluded that the data variances for both groups were homogeneous. Thus, the data satisfied the assumptions of normality and homogeneity, allowing the analysis to proceed using an independent-samples t-test.

The independent-samples t-test results yielded a t-value of 8.74 with a significance level of $p = 0.000$. Since $p < 0.05$, the null hypothesis (H_0) was rejected. Consequently, there was a statistically significant difference in critical thinking skills between the experimental and control groups following the intervention. This difference was also evident in the descriptive post-test means: the experimental group achieved an average of 79.17, whereas the control group scored 61.50. Thus, the experimental group's average critical thinking score was 17.67 points higher than that of the control group. These results indicate that the difference in critical thinking skills following instruction was not merely reflected in the mean scores but was also supported by statistical analysis. Therefore, the implementation of AI-integrated PjBL resulted in significantly higher critical thinking skills compared to conventional instruction among the students participating in the study.

Discussion

1. Enhancing Students' Critical Thinking Skills through AI-Integrated Project-Based Learning (PjBL)

Research findings indicate that the implementation of an Artificial Intelligence (AI)-integrated Project-Based Learning (PjBL) model yields a greater improvement in critical thinking skills compared to conventional instruction. The average critical thinking score for the experimental group rose from 48.33 in the pretest to 79.17 in the posttest, whereas the control group increased from 47.67 to 61.50. Consequently, the score increase for the experimental group was 30.84 points, compared to only 13.83 points for the control group. This difference in improvement demonstrates that instruction allowing students to actively engage in inquiry, problem-solving, decision-making, and product creation holds greater potential for developing critical thinking skills.

These findings align with systematic reviews of problem- and project-based learning environments, which indicate that exposing students to authentic problems, collaborative activities, investigations, and project-completion processes can foster the development of higher-order thinking and critical thinking skills (Loyens et al., 2023). These reviews confirm that the key characteristics of P(j)BL—particularly student engagement with problems and collaboration—create learning conditions that enable critical thinking processes to flourish.

The findings of this study also reinforce empirical evidence that PjBL is relevant for science instruction in elementary schools. Meta-analyses regarding PjBL in elementary science education indicate that project-based learning can enhance critical thinking skills through problem-solving activities and student engagement in the learning process. Thus, the score improvements observed in the experimental group in this study can be attributed not only to the use of AI technology but also to the characteristics of PjBL, which position students as the central agents of the learning process.

Pedagogically, PjBL enables students to transition from merely understanding information to applying it to solve real-world problems. In this study, the Natural and Social Sciences (IPAS) curriculum regarding ecosystems and environmental balance provided a context that allowed students to identify environmental issues, gather information, analyze cause-and-effect relationships, design solutions, create products, and evaluate project outcomes. This sequence of activities directly offered students opportunities to exercise skills in interpretation, analysis, evaluation, inference, and explanation—all of which served as indicators of critical thinking in this study. These findings are particularly relevant given that research on project-based learning demonstrates a link between metacognitive abilities, creativity, and critical thinking, especially when projects address environmental issues. Environmentally oriented projects can create learning situations that require students to connect knowledge with real-world conditions, evaluate various alternatives, and justify the decisions they make.

The greater improvement observed in the experimental group is also linked to how AI was integrated into the stages of Project-Based Learning (PjBL). In this study, AI served not merely as a medium for content delivery but as a support tool across the stages of problem formulation, project planning, information exploration, feedback provision, evaluation, and reflection. This approach enabled students to access information and feedback more rapidly while simultaneously requiring them to scrutinize and evaluate the information provided by the AI.

These findings align with the results of a systematic review regarding the use of AI in science education. Almasri (2024) demonstrated that AI in science education has been utilized for various pedagogical functions, including supporting learning environments, providing feedback, conducting assessments, generating learning activities, and helping students grasp complex concepts. The study further indicated that AI can benefit the learning process when implemented as part of a well-planned pedagogical environment.

In the context of this study, the benefits of AI lie not merely in the technology's ability to generate information, but in the opportunities it affords students to interact with information, question answers, compare sources, and make evidence-based decisions. Thus, AI serves as a cognitive scaffold that assists students when they encounter difficulties during the project. This is significant because the unrestricted use of AI does not automatically lead to enhanced critical thinking. Recent studies on generative AI indicate that it possesses a dual nature. On one hand, AI can support analysis, reasoning, evaluation, decision-making, problem-solving, creativity, and independent learning. On the other hand, over-reliance on AI can foster passive thinking, reduce the depth of analysis, and hinder the development of cognitive independence (Liu et al., 2025).

Therefore, the results of this study can be understood through the principle of AI-supported but human-guided learning. AI provides informational support and feedback, while students remain the ones who determine whether the information is accurate, relevant, and applicable to solving the problem. This pattern is a key aspect distinguishing the pedagogical use of AI from its use merely as a tool for obtaining answers.

A key aspect of this study is that students are guided not to accept AI-generated information at face value. When AI is used to provide alternative answers, explanations, or solutions, students are encouraged to compare them against observations, learning resources, and other available information. This activity likely accounts for the improvement in critical thinking skills observed in the experimental group. Students do not merely acquire information; they must address questions such as: Is the

information accurate? What is the evidence? Does it align with the observed environmental conditions? Is there conflicting information? Which solution is the most appropriate? Thus, interacting with AI creates additional opportunities for evaluation. These findings align with recent research indicating that in Generative AI (GenAI)-based learning environments, critical thinking is increasingly linked to students' ability to detect AI errors, evaluate information credibility, and verify sources (Cong-Lem & Thuy-Dung, 2025).

A study by Liu et al. (2025) also indicates that generative AI can support analytical thinking, reasoning, evaluation, decision-making, and problem-solving when used purposefully. However, these benefits can turn into risks if students become overly reliant on AI-generated output. Therefore, the enhancement of critical thinking in this study is more accurately attributed to the students' patterns of interaction with AI—specifically those involving verification and evaluation tasks—rather than merely the presence of AI itself. The research instrument measures five critical thinking indicators: interpretation, analysis, evaluation, inference, and explanation. These five indicators are closely linked to the stages of Project-Based Learning (PjBL). In the initial stage, students must interpret the environmental issues they encounter; they need to comprehend preliminary information, identify environmental conditions, and determine the specific problem to be investigated. Subsequently, during the investigation stage, students conduct an analysis by connecting various pieces of information and identifying factors related to the problem.

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The evaluation stage occurs when students compare various information alternatives and solutions, including contrasting AI-generated information with their own observations and other sources. Subsequently, students engage in inference by drawing conclusions based on the evidence gathered. The final stage comprising presentation and reflection offers students the opportunity to develop their explanatory skills, specifically by articulating the rationale, evidence, processes, and conclusions associated with their project. Thus, the five critical thinking indicators are not cultivated through isolated exercises but rather through a series of authentic project-based activities. This aligns with the findings of Loyens et al. (2023), who noted that Project-Based Learning (PjBL) environments possess characteristics that foster critical thinking development through problem-solving, collaboration, inquiry, and high-level cognitive activities.

The difference in outcomes between the two groups can be attributed to differences in the characteristics of learning activities. Conventional instruction in this study relied heavily on teacher explanations, question-and-answer sessions, textbook-based exercises, individual assignments, and discussions. While these activities provided learning opportunities, the scope for students to conduct authentic investigations, develop products, evaluate alternatives, and engage in reflection was relatively limited. In contrast, AI-integrated PjBL creates a cycle of: problem → inquiry → information → analysis → solution → product → evaluation → reflection. This cycle encourages students to actively apply their knowledge. Furthermore, AI integration expands the range of information sources and provides feedback that students can use to refine both their processes and their project products.

A systematic review of AI in science learning indicates that AI can support various learning functions, including the provision of feedback, assessment, learning activities, and conceptual understanding. Meanwhile, studies on Generative AI (GenAI) in K–12 education show that AI implementation is rapidly evolving, yet its success hinges largely on how the technology is integrated into the pedagogical process. Thus, the effectiveness of the intervention in this study likely stems not from AI in isolation, but from the synergy between the PjBL pedagogical structure and AI's supportive

functions. PjBL provides the context and cognitive demands, while AI offers the informational support and feedback that assist students in navigating the process.

The research findings also hold significant implications for the teacher's role in AI-based learning. AI should not replace teachers or usurp students' decision-making processes. Instead, teachers act as designers of learning experiences, facilitators, monitors of AI usage, and providers of scaffolding. This aligns with recent developments in educational AI research. A systematic review of Generative AI (GenAI) in K–12 education indicates that AI implementation must take into account pedagogical design, teacher involvement, learner characteristics, and the risk of technological dependency. A study by Liu et al. (2025) also highlights the dual nature of GenAI usage: while most of the studies they reviewed identified positive potential regarding critical thinking, others revealed risks such as over-reliance, passive thinking, and reduced depth of analysis. Therefore, the approach taken in this study positioning students as examiners and evaluators of information represents a crucial aspect that should be maintained within the learning model.

The research findings have specific implications for IPAS (Natural and Social Sciences) instruction. IPAS content—particularly topics related to the environment, ecosystems, environmental changes, and daily life—provides a robust context for developing project-based learning. In the context of this study, issues within the school environment can serve as a bridge between IPAS concepts and real-life situations. Students do not merely learn definitions of ecosystems, food chains, or environmental balance; rather, they apply these concepts to explain phenomena observed in their immediate surroundings. This approach aligns with the nature of science education, which aims not only to foster conceptual mastery but also to develop the ability to use knowledge for scientific reasoning and decision-making. A systematic review by Almasri (2024) indicates that integrating AI into science education can support the learning process and offer opportunities to enrich the learning environment. Consequently, integrating Project-Based Learning (PjBL) and AI into IPAS instruction can be directed toward not only enhancing cognitive learning outcomes but also fostering scientific literacy, problem-solving skills, the ability to evaluate digital information, and evidence-based decision-making capabilities.

Although the research findings indicate a strong effect, several limitations should be noted. First, the study involved only 60 students from two classes; therefore, generalizing the results requires caution. Second, the sample was selected using purposive sampling based on technological readiness, meaning the characteristics of the students and schools may not be representative of the broader landscape of primary schools. Third, the intervention spanned only eight sessions, so it could not determine the long-term impact of AI usage on critical thinking skills. Fourth, the success of AI integration relied heavily on internet connection quality, device availability, teacher competence, and students' ability to evaluate AI-generated information. Fifth, the study examined AI-integrated PjBL as a single intervention package, making it impossible to isolate the respective contributions of PjBL and AI. To address this, future research could employ a factorial design—for instance, by comparing PjBL without AI, PjBL with AI, conventional instruction without AI, and conventional instruction with AI.

CONCLUSION

Based on the research results and discussion, it can be concluded that the implementation of Project-Based Learning (PjBL) integrated with Artificial Intelligence (AI) yields better results in enhancing the critical thinking skills of elementary school students compared to conventional instruction. This conclusion is based on three key findings.

First, students' critical thinking skills improved following the implementation of AI-integrated PjBL. The average critical thinking score for the experimental group rose from 48.33 in the pretest to 79.17 in the posttest, with an N-gain value of 0.68. Meanwhile, the control group's score increased from 47.67 to 61.50, with an N-gain of 0.33. These results indicate that the improvement in critical thinking skills was greater in the experimental group than in the control group.

Second, there is a significant difference in students' critical thinking skills between the experimental and control groups following the intervention. The independent-samples t-test

results yielded a t-value of 8.74 ($p < 0.001$), leading to the rejection of the null hypothesis. Thus, AI-integrated PjBL instruction resulted in statistically higher critical thinking skill outcomes compared to conventional instruction.

Third, based on N-gain analysis, AI-integrated PjBL instruction demonstrated greater effectiveness in fostering improvement than conventional instruction. The N-gain value for the experimental group was 0.68, whereas that of the control group was 0.33. Furthermore, the Cohen's d estimate of 2.26 indicates a very large effect size, signifying that the difference in outcomes between the two groups is not only statistically significant but also holds substantial practical significance.

Overall, the research findings indicate that integrating AI into PjBL has the potential to be an effective learning strategy for enhancing the critical thinking skills of elementary school students—particularly when AI supports information exploration, feedback, evaluation, and reflection, while students remain actively engaged in analyzing, verifying, evaluating, and utilizing information to complete projects.

Consequently, elementary school teachers might consider implementing AI-integrated PjBL in Science and Social Studies (IPAS) lessons that address authentic issues, such as ecosystems, environmental balance, and environmental change. However, the use of AI requires teacher guidance and information verification activities to ensure that technology does not replace the students' own thinking processes. Generalizing the research findings requires caution, as the study involved 60 students from two classes selected via purposive sampling and was conducted over eight sessions. Future research should involve a broader and more diverse sample, employ a longer intervention period, and compare PjBL with and without AI to identify AI's specific contribution to the development of critical thinking skills. Subsequent studies should also analyze changes in each critical thinking indicator—interpretation, analysis, evaluation, inference, and explanation and utilize statistical analysis that controls for students' initial proficiency, provided individual data is available.

Conflict Of Interest

The authors declare no conflict of interest.

Generative AI Statement

In the preparation of this manuscript, AI-assisted tools were employed solely for limited linguistic refinement and stylistic enhancement. The development of the conceptual framework, data interpretation, methodological design, and all substantive scholarly content was independently undertaken and critically reviewed by the authors. The authors assume full responsibility for the accuracy, integrity, and final content of the manuscript.

Author Contribution Statement

I Dewa Ketut Artha Saputra: Conceptualization, methodology, development of research instruments, data collection, data curation, formal analysis, interpretation of findings, writing—original draft, and manuscript revision. I Wayan Darmayoga: Conceptualization, validation of the research design and methodology, supervision, interpretation of findings, writing review and editing, and final manuscript validation.

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