Published online on the page : https://journal.makwafoundation.org/index.php/edusains

Journal of Education and Science
(E D U S A I N S)
|ISSN (Online) 3030-8267 |

Project-Based Learning and Elementary Students' Mathematical Critical Thinking: A Quasi-Experimental Study

Nurlev Avana[1]*, Opi Andriani[2] , Muhammad Subhan[3], Aldino[4], Dhini Mufti[5] , Aprinaldo[6], Rhomiy Handican[7]

[1,2,3,4,5,6]*Universitas Muhammadiyah Muara Bungo, Bungo,* Indonesia
[7]*Institut Agama Islam Negeri Kerinci, Sungai Penuh,* Indonesia

Article Information

Article History
Received: April 1, 2026
Revised: April 16, 2026
Accepted: May 20, 2026
Published: June 30, 2026

Kata Kunci

Mathematical Critical Thinking, Project-Based Learning, Elementary Mathematics Education, Higher-Order Thinking Skills.

Correspondence

E-mail:

avananurlev10@gmail.com*

A B S T R A C T

Mathematical critical thinking is an essential competency that enables elementary students to analyze information, evaluate alternative solutions, and make reasoned decisions when solving mathematical problems. This study examined differences in mathematical critical-thinking performance between elementary students who learned through Project-Based Learning (PjBL) and those who received conventional instruction. A quasi-experimental study employing a posttest-only control group design involved 40 sixth-grade students, comprising 20 students in the experimental group and 20 in the control group. The experimental group received PjBL-based mathematics instruction, whereas the control group received conventional instruction. Data were collected using an essay-based mathematical critical-thinking test and analyzed using Welch's independent-samples t-test to account for unequal variances between the groups. The results indicated a statistically significant difference in posttest scores, $t(27.36) = 18.42$, $p < .001$, *with a mean difference of 25.40 points (95% CI [22.57, 28.23]). The experimental group achieved a higher mean score* ($M = 90.0$) *than the control group* ($M = 64.6$), *with a very large effect size (Hedges'* $g = 5.71$). *These findings indicate that students who participated in PjBL demonstrated substantially higher observed mathematical critical-thinking performance than those who received conventional instruction. This study provides context-specific empirical evidence supporting the use of carefully designed PjBL in elementary mathematics, particularly when project activities are aligned with mathematical learning objectives and supported by appropriate teacher guidance.*

This is an open access article under the CC–BY-SA license

1. Introduction

The development of higher-order thinking skills has become a fundamental priority in contemporary education. Educational systems are increasingly expected to prepare students not only to acquire and reproduce knowledge but also to analyze information, evaluate alternatives, solve unfamiliar problems, and make reasoned decisions (Ismael et al., 2026; Prasetyo et al., 2026) . This expectation is particularly relevant to mathematics education because mathematical learning requires students to identify patterns, examine relationships, construct logical arguments, and justify conclusions. International educational frameworks have emphasized the importance of applying knowledge and reasoning to complex situations rather than merely recalling previously learned information (Koedinger et al., 2012) . Research on higher-order and critical thinking has similarly demonstrated that meaningful learning should provide students with opportunities to engage in analysis, evaluation, reflection, and reasoning (Agustini et al., 2024; Darwis et al., 2024; Manalu et al., 2025; Mulyawati1 et al., n.d.) . Furthermore, evidence from research on active and cognitively demanding learning environments suggests that students develop deeper understanding when they participate directly in knowledge construction and

 Creative Commons Attribution-ShareAlike 4.0 International License. *Some rights reserved*

problem solving (Darwis et al., 2024; Rossi et al., 2021) . Consequently, mathematics instruction should provide learning experiences that encourage students to think beyond procedural performance and engage actively in meaningful reasoning processes.

Mathematical critical thinking represents an essential dimension of mathematics learning because successful mathematical performance involves more than obtaining a correct numerical answer. Students are expected to interpret information, identify relevant mathematical relationships, evaluate the appropriateness of possible strategies, and justify the conclusions they reach (Malau et al., 2025; Purnamasari et al., 2026) . These abilities enable students to approach mathematical problems reflectively rather than simply searching for familiar formulas or procedures. Research on mathematical reasoning has emphasized that meaningful mathematics learning requires students to explain why a particular strategy is appropriate and to evaluate whether alternative approaches may also produce valid solutions (Koskinen & Pitkäniemi, 2022; Mawardha et al., 2026; Payaseunara et al., 2025) . Studies on mathematical critical thinking further indicate that students' reasoning develops when they are provided with opportunities to analyze problems, construct arguments, and communicate their ideas (Apriliandi, 2025; Aridanthy et al., 2026; Izzati & Suryadi, 2026) . Evidence from Indonesian mathematics education has also highlighted the importance of instructional activities that encourage students to engage actively with mathematical problems rather than merely reproduce teacher-demonstrated procedures (Shoffa et al., 2026) . Thus, mathematical critical thinking should be considered an integral outcome of mathematics education, particularly in learning environments intended to develop students' analytical and reflective capacities.

The development of mathematical critical thinking is particularly important during elementary education because this period provides a foundation for students' subsequent mathematical understanding and reasoning. Elementary school students are developing fundamental concepts, cognitive structures, and attitudes toward mathematics that may influence how they approach increasingly complex problems in later educational stages (Fitri Yabashiru et al., 2025; Oktaviani et al., 2023) . When learning is dominated by memorization and repetitive exercises, students may perceive mathematics primarily as a collection of fixed rules that must be followed to obtain predetermined answers. In contrast, learning activities that encourage students to investigate problems, explain their ideas, compare strategies, and evaluate solutions can promote more active forms of mathematical reasoning (Hadi et al., 2025; Wahyuningrum et al., 2024) . Research on elementary students' critical thinking has similarly emphasized the importance of instructional environments that engage learners in inquiry, decision-making, and reflection (Masithoh et al., 2025) . Recent evidence concerning mathematical learning in elementary education also suggests that contextual and problem-oriented activities can provide meaningful opportunities for students to develop analytical thinking while connecting mathematical knowledge with practical situations (Basid et al., 2024) . Therefore, the elementary-school period represents a particularly important stage for establishing learning habits that support mathematical critical thinking.

Despite its importance, the development of mathematical critical thinking remains challenging in many classrooms. Conventional mathematics instruction frequently emphasizes teacher explanations, demonstrations of solution procedures, and repeated exercises designed to reinforce predetermined methods. Although such approaches can

contribute to procedural fluency, excessive dependence on teacher-centered instruction may limit opportunities for students to formulate questions, investigate mathematical relationships independently, compare alternative strategies, and evaluate their own reasoning (Osborne, 2021) . Research examining critical thinking in elementary education has identified the lack of learning activities involving authentic problems and analytical decision-making as an important challenge (Fitriadi et al., 2024) . Evidence from mathematics education also suggests that students' higher-order thinking may be constrained when classroom activities focus predominantly on routine procedures rather than exploration and reasoning (Gradini et al., 2025). Studies investigating instructional interventions for critical thinking have therefore emphasized the importance of learning environments in which students actively participate in problem analysis and solution development (Dewi et al., 2025) . These limitations have encouraged mathematics educators to explore instructional approaches capable of creating more active, contextual, and cognitively demanding learning experiences.

One instructional approach that offers considerable potential in this regard is Project-Based Learning (PjBL). PjBL organizes learning around meaningful questions, authentic problems, or challenging tasks that require students to engage in sustained inquiry and develop a meaningful outcome, such as a product, solution, report, or presentation. Project-oriented learning positions students as active participants who investigate problems, gather information, plan activities, collaborate with peers, make decisions, and evaluate the outcomes of their work (Mustamin et al., 2024) . This approach differs substantially from conventional instruction because students are not expected merely to receive information and reproduce previously demonstrated procedures. Instead, they participate directly in processes of inquiry and knowledge construction. Research involving elementary and basic education has suggested that PjBL can provide meaningful learning experiences when projects are connected clearly with learning objectives and supported through appropriate instructional guidance (Almulla, 2020; Isnani, 2023) . Moreover, systematic evidence has shown that the implementation of PjBL requires careful attention to project design, student participation, and teacher scaffolding to ensure that learning activities produce meaningful educational outcomes (Listiana et al., 2025) .

The theoretical relevance of PjBL to mathematical critical thinking lies in the cognitive processes embedded throughout project activities. Students involved in projects are often required to identify problems, determine relevant information, analyze relationships, compare possible strategies, make decisions, and evaluate the feasibility of their solutions. These processes are closely associated with critical thinking because students must use evidence and reasoning rather than simply reproduce predetermined answers. Research examining Project-Based Learning has shown that inquiry, problem solving, collaboration, and reflection constitute important mechanisms through which project activities can support students' higher-order thinking (Anchunda & Kaewurai, 2025; Mufadilah et al., 2025; Mukaromah et al., 2021) . A systematic review focusing specifically on the relationship between PjBL and mathematical critical thinking similarly identified project planning, collaborative work, evaluation, and reflection as important components supporting students' analytical and argumentative abilities (Auliyani et al., 2025; Yusri et al., 2024) . Recent research involving elementary education has also reported that project-oriented activities can encourage students to analyze information, evaluate possible solutions, and construct logical responses to meaningful challenges (Eshun et al., 2026) . Therefore, the potential value of PjBL extends

beyond the production of a final project because the learning process itself can create opportunities for sustained reasoning and critical engagement.

The effectiveness of PjBL has received substantial attention in educational research. Meta-analytic evidence generally indicates that Project-Based Learning can positively influence students' academic and cognitive outcomes when compared with more conventional instructional approaches (Rehman et al., 2024). Recent higher-level evidence synthesizing multiple meta-analyses likewise reports a generally positive direction of PjBL effects on academic achievement and higher-order thinking, while also cautioning that the precise magnitude of these effects remains dependent on the quality and heterogeneity of the available evidence (Nurkanti et al., 2025). Research specifically involving kindergarten and elementary students, however, has provided a more cautious interpretation, emphasizing that evidence in basic education remains limited and that the quality of implementation plays an important role in determining outcomes (Ferrero et al., 2021) . These findings suggest that PjBL should not be viewed as an automatically effective instructional model; rather, its effectiveness depends substantially on how projects are designed, implemented, and supported within particular educational contexts.

The implementation of PjBL is especially relevant to mathematics education because mathematics is often perceived as an abstract subject consisting primarily of symbols, formulas, and computational procedures. Although abstraction is an essential characteristic of mathematical knowledge, students may experience difficulty when mathematical concepts are presented without meaningful opportunities for interpretation and application. Project activities can potentially address this limitation by positioning mathematics as a tool for investigating real or meaningful situations, analyzing quantitative relationships, and developing solutions. A systematic review of PjBL in mathematics education reported that project-oriented learning can promote collaboration, problem solving, and critical thinking by connecting mathematical knowledge with active inquiry (Dahal & G.C., 2026) . Previous research has also shown that project-based mathematical activities can create opportunities for students to apply concepts in contextual situations rather than treating mathematical procedures as isolated skills (Abdul Halim, 2025) . Furthermore, studies on mathematical critical thinking indicate that contextual problem engagement can encourage students to analyze information and evaluate solution strategies more carefully (Malau et al., 2025) . Accordingly, PjBL may provide an instructional environment in which mathematical knowledge is used as a meaningful instrument for reasoning and problem solving.

The potential benefits of PjBL are also supported by an expanding body of research in the Indonesian educational context. Indonesian studies have increasingly examined project-oriented learning as an approach for promoting critical thinking through inquiry, collaboration, problem solving, and reflection (Dahal & G.C., 2026; Eshun et al., 2026; Mukaromah et al., 2021) . Research focusing specifically on elementary school students has reported that PjBL can encourage active participation and support students in developing the ability to analyze and evaluate problems (Fitri Yabashiru et al., 2025; Mulyawati1 et al., n.d.) . Evidence concerning mathematical critical thinking among Indonesian primary school students also demonstrates that active learning approaches can contribute to stronger analytical reasoning, although instructional outcomes may vary according to factors such as treatment duration, classroom characteristics, and mathematical topics (Apriliandi, 2025; Rehman et al., 2023) .

These findings indicate that the potential relationship between active learning and critical thinking is highly relevant to Indonesian elementary education and requires continued empirical investigation within specific mathematics learning contexts.

Nevertheless, the growing body of evidence on Project-Based Learning (PjBL) does not indicate that its educational outcomes are uniform across contexts, learning objectives, or implementation configurations. Research in primary mathematics has reported positive differences in critical thinking following PjBL, including studies using quasi-experimental designs and comparisons with conventional instruction. For example, Rehman et al. reported significant differences in critical thinking among primary students learning mathematics through PjBL, while he found differences in mathematics learning outcomes and critical thinking in an elementary-school quasi-experimental study (Rehman et al., 2023). More recent research has examined PjBL combined with augmented reality to support mathematical critical thinking, whereas other studies have focused on creative thinking and mathematical problem solving rather than mathematical critical thinking as the primary outcome (Fatahillah & Faradillah, 2023). These studies collectively provide promising evidence, but they also demonstrate considerable variation in student populations, mathematical content, intervention configurations, outcome measures, and research designs.

This heterogeneity suggests that the relevant research question is no longer simply whether PjBL can be associated with positive learning outcomes, but how consistently its use is related to mathematical critical-thinking performance when mathematical critical thinking is examined as a specific outcome in elementary mathematics learning. Recent systematic evidence indicates that the effects of PjBL in kindergarten and elementary education remain sensitive to implementation quality, the fidelity of the intervention, and the adequacy of instructional procedures and support provided to students and teachers (Ferrero et al., 2021) . Recent evidence syntheses also report that critical thinking is among the outcomes commonly examined in elementary PjBL research, with reported benefits involving students' abilities to analyze, evaluate, and solve problems (Dinda Antika Putri et al., 2025). However, studies in elementary mathematics have investigated different outcomes, including creative thinking and mathematical problem-solving skills, rather than mathematical critical thinking as the sole or primary outcome (Ndiung & Menggo, 2024) . Moreover, recent studies have increasingly incorporated additional components into PjBL, such as augmented reality(Fatahillah & Faradillah, 2023) , STEM-oriented learning designs (Prastiti et al., 2026), and culturally contextualized or ethnomathematics-based projects (Susanto et al., 2021) . These variations in outcome focus and intervention configuration make it difficult to determine the empirical contribution of PjBL itself when additional technological, interdisciplinary, or cultural components are simultaneously embedded in the intervention.

Against this background, the present study is positioned as a focused empirical comparison rather than as a proposal of a new theoretical model. Previous research has demonstrated the potential of PjBL to support critical thinking and other higher-order skills in primary mathematics, but these studies have differed in intervention design, outcome focus, and the use of additional instructional components (Dinda Antika Putri et al., 2025; Ndiung & Menggo, 2024; Rehman et al., 2024) . The present study examines whether elementary students who participate in mathematics learning through PjBL demonstrate different mathematical critical-thinking performance from students who receive conventional instruction. The

investigation focuses specifically on mathematics learning involving line diagrams and uses an essay-based assessment of mathematical critical thinking administered after the instructional intervention. This positioning responds to the heterogeneity identified in previous research by examining PjBL as the principal instructional condition and mathematical critical thinking as the central learning outcome, without introducing additional instructional components such as STEM, augmented reality, or ethnomathematical integration (Nurlaela et al., 2025; Susanto et al., 2021) . The contribution of the study is therefore primarily empirical and pedagogical: it provides context-specific evidence on differences in mathematical critical-thinking performance between PjBL and conventional mathematics instruction in elementary education and offers evidence that may inform the design of project-oriented mathematics instruction.

Accordingly, this study aims to examine whether there is a statistically significant difference in mathematical critical-thinking performance between elementary students who learn mathematics through Project-Based Learning and those who receive conventional mathematics instruction. The study does not seek to establish a general causal mechanism through which collaboration, motivation, autonomy, reflection, or engagement produces changes in critical thinking, because these processes are not independently measured in the present design. Instead, the study focuses on the observable difference in posttest mathematical critical-thinking performance between the two instructional groups. This analytical focus is consistent with previous empirical research showing that PjBL can be associated with differences in critical thinking and other higher-order outcomes, while systematic reviews emphasize variation in implementation and outcome measures across studies (Dinda Antika Putri et al., 2025; Ferrero et al., 2021; Rehman et al., 2023) .Accordingly, the findings are interpreted as context-specific empirical evidence concerning differences in mathematical critical-thinking performance between students experiencing PjBL and those receiving conventional instruction, rather than as evidence of a universally applicable causal mechanism.

2. Method

2.1 Research Design

This study employed a quasi-experimental posttest-only control-group design to examine differences in mathematical critical-thinking performance between elementary students receiving Project-Based Learning (PjBL) and those receiving conventional mathematics instruction. The study involved all 40 sixth-grade students available in one classroom at the selected elementary school. No students from this classroom were excluded from the initial participant pool. Before the intervention, all 40 students completed an initial mathematics diagnostic test. The diagnostic scores were then ranked from the highest to the lowest. Students were subsequently distributed alternately between the experimental and control groups based on this ranking until each group consisted of 20 students. This rank-order allocation procedure was intended to achieve a relatively balanced distribution of students' initial mathematical proficiency between the two groups. However, the allocation did not involve individual random assignment.

The experimental group received mathematics instruction using the Project-Based Learning (PjBL) approach, whereas the control group received conventional teacher-led mathematics instruction. The two groups participated in separate instructional sessions

conducted at different times and facilitated by different teachers. Both groups studied the same mathematical topic, namely line diagrams, and completed the same essay-based mathematical critical-thinking posttest following the instructional intervention.

Table 1. Research Design

Group	Treatment	Posttest
Experimental Group	X	O_1
Control Group	–	O_2

Note:

X = Mathematics instruction using the Project-Based Learning model

– = Conventional mathematics instruction

O_1 = Posttest of the experimental group

O_2 = Posttest of the control group

The initial diagnostic assessment was used to guide group allocation and examine differences in students' initial mathematical proficiency. However, it did not directly measure the primary outcome of mathematical critical thinking. Consequently, the diagnostic results cannot establish baseline equivalence in the specific outcome investigated in this study. Furthermore, the use of different teachers and separate instructional schedules introduced potential instructor-related and instructional-context differences that may have influenced students' posttest performance. Therefore, the findings are interpreted as differences in observed post-intervention performance between the two instructional groups rather than definitive evidence of an isolated causal effect of PjBL.

2.2 Participants and Research Setting

The study was conducted at SD Negeri No. 100/II Muara Bungo, a public elementary school in Muara Bungo Regency, Jambi Province, Indonesia. The participants comprised all 40 sixth-grade students aged 11–12 years in the selected classroom. All available students in this classroom were included in the study; therefore, no individual purposive selection was conducted within the classroom. Before the instructional intervention, all 40 students completed an initial mathematics diagnostic assessment. To distribute the students between the two instructional groups, their diagnostic scores were ranked from the highest to the lowest. Students were then assigned alternately to the experimental and control groups according to their ranking until each group contained 20 students. This procedure was intended to distribute students with different levels of initial mathematical proficiency relatively evenly between the two groups. The experimental group received Project-Based Learning (PjBL)-based mathematics instruction, while the control group received conventional mathematics instruction.

The diagnostic test results for the cohort showed a mean score of 74.30 and a modal score of 72.50. An independent-samples t-test comparing the diagnostic scores of the two groups yielded $t(38) = 1.191$, $p = .241$, with a mean difference of 2.80 and a 95% confidence interval ranging from −1.96 to 7.56. Thus, the analysis did not detect a statistically significant difference between the groups in their initial basic mathematics diagnostic scores. Nevertheless, this finding should not be interpreted as proof of statistical equivalence, particularly because the diagnostic assessment did not measure mathematical critical thinking, the primary outcome of the study. All 40 students completed the scheduled intervention and posttest sessions, and no outcome observations were missing. The study was conducted within a single classroom

in one elementary school, and the allocation procedure did not involve individual random assignment. These characteristics, together with the absence of a pretest measuring mathematical critical thinking and the use of different teachers and instructional schedules, limit the strength of causal interpretations and the generalizability of the findings. Therefore, the findings should be interpreted as context-specific evidence of differences in observed posttest performance between the two instructional groups.

2.3 Research Procedure

The research was conducted over six instructional sessions, with each session lasting 2 × 35 minutes. Before the intervention, all 40 students completed an initial mathematics diagnostic test. Based on the diagnostic results, students were allocated into two groups of equal size, comprising 20 students in the experimental group and 20 students in the control group. The allocation was intended to achieve a relatively balanced distribution of students' initial mathematical proficiency between the groups.

The two groups received instruction separately at different scheduled times and were taught by different teachers. The experimental group received mathematics instruction through the Project-Based Learning (PjBL) approach, while the control group received conventional teacher-led mathematics instruction using the lecture method. Both groups studied the same topic, namely line diagrams, and participated in six instructional sessions. Following the completion of the intervention, students in both groups completed the same essay-based mathematical critical-thinking posttest. In the experimental group, PjBL was implemented through six stages: formulating essential questions, designing the project, developing a project schedule, monitoring students and project progress, evaluating project outcomes, and presenting the completed project. Students worked collaboratively on a project involving the construction and interpretation of line diagrams. The implementation of the instructional activities was monitored by an external observer using a classroom observation checklist covering three aspects: model syntax, social system, and reaction principles. In contrast, the control group received conventional mathematics instruction through teacher-led explanations and classroom exercises rather than project-based activities. Because the two instructional groups were taught by different teachers and at different times, differences in teacher-related instructional practices and scheduling conditions may have contributed to the observed outcomes. This consideration was taken into account when interpreting the findings and acknowledging the methodological limitations of the study.

2.4 Research Instrument

The primary instrument used to measure students' mathematical critical-thinking skills was an essay-based test focusing on line diagrams. The initial instrument consisted of 15 essay items developed in accordance with the learning objectives and the four indicators of mathematical critical thinking adopted from Facione's framework (Facione, 2015) : interpretation, analysis, evaluation, and inference. The essay format was selected to allow students to demonstrate their mathematical reasoning, provide explanations, and support their answers with relevant arguments rather than merely selecting predetermined responses.

Before the main study, the initial 15-item instrument was pilot-tested on 14 participants who were not included in the research sample. The pilot-test data were analyzed in terms of item validity, test reliability, item difficulty, and discrimination power. The internal

consistency of the instrument was examined using Cronbach's Alpha, which yielded a coefficient of 0.846. These analyses provided an empirical basis for evaluating the quality of each item and determining its suitability for inclusion in the final instrument. Based on the combined item-analysis results, 11 items were retained, while four items (Items 1, 10, 13, and 15) were excluded. The selection procedure considered not only the validity coefficients but also the difficulty level and the ability of each item to distinguish between students with different levels of mathematical performance.

Each retained item was assessed using the four mathematical critical-thinking indicators, with a maximum score of 4 points for each indicator. Consequently, each item had a maximum score of 16, and the final 11-item instrument had a maximum possible raw score of 176. A five-level scoring rubric, ranging from 0 to 4, was used to evaluate students' responses. A score of 0 indicated the absence of a relevant response or evidence of the assessed indicator; a score of 1 represented a very limited and largely inaccurate response; a score of 2 indicated a partially correct response with incomplete reasoning or evidence; a score of 3 represented a correct and reasonably logical response with relevant reasoning but minor shortcomings; and a score of 4 indicated an accurate response supported by clear argumentation and relevant reasoning or evidence. The scoring rubric had been validated before its use in assessing students' responses.

To promote scoring consistency, the researcher and the classroom teacher independently assessed students' responses using the previously validated scoring rubric. After completing their individual assessments, they compared their scoring results to identify differences in the interpretation and application of the assessment criteria. This procedure was intended to support consistency in applying the rubric across students' responses. The same final test, assessment indicators, and scoring rubric were applied to both the experimental and control groups. Raw test scores were converted to a 0–100 scale using the following formula:

$$\left[\text{Score} = \frac{\text{Obtained score}}{176} \times 100\right]$$

This conversion enabled students' mathematical critical-thinking performance to be reported on a standardized scale.

2.5 *Data Collection*

The primary quantitative data were obtained from students' responses to the final essay-based mathematical critical-thinking posttest administered to both the experimental and control groups after the six-session instructional intervention. The same 11-item test was used for both groups. Each item had a maximum score of 16, resulting in a maximum total raw score of 176. The raw scores were converted to a 0–100 scale for reporting and comparison. Students' responses were assessed using the four indicators of critical thinking: interpretation, analysis, evaluation, and inference.

Supplementary data were collected through classroom observations, teacher interviews, and documentation. Classroom observations were conducted by an external observer, who served as a field research assistant, using an observation checklist. The checklist assessed three aspects of instructional implementation: model syntax, social system, and reaction principles. The observation results were summarized descriptively to document the extent to which the planned instructional activities were implemented. Teacher interviews provided contextual

information about the instructional process, while documentation supported the recording of relevant learning activities and implementation-related information.

These supplementary sources served a supporting role in describing and contextualizing the implementation of the instructional conditions rather than functioning as independent outcome measures. They were not subjected to a separate qualitative analysis. Accordingly, the primary comparison of students' mathematical critical-thinking performance was based on the posttest data, while the observation results and other supplementary information provided contextual evidence concerning the implementation of the instructional activities.

2.6 *Data Analysis*

The quantitative data were analyzed using IBM SPSS Statistics version 27. Descriptive statistics, including the mean, standard deviation, minimum, and maximum scores, were calculated to summarize the mathematical critical-thinking posttest performance of the experimental and control groups. Before inferential analysis, the distribution of posttest scores in each group was examined using the Shapiro–Wilk test. Levene's test was used to assess the homogeneity of variances between the groups.

Welch's independent-samples *t*-test was used to compare the mean posttest scores of the two independent groups because Levene's test indicated that the assumption of equal variances was not satisfied. The statistical significance level was set at .05. The analysis included the *t* statistic, degrees of freedom, *p* value, mean difference, and 95% confidence interval for the mean difference. Hedges' *g* was also reported as a standardized estimate of the magnitude of the observed difference between groups.

Supplementary classroom observation data were summarized descriptively to document the implementation of the planned instructional activities. Teacher interviews and documentation were used to provide contextual information about the instructional process rather than as independent outcome measures. These supplementary data were not subjected to a separate qualitative analysis. The primary comparison therefore relied on students' mathematical critical-thinking posttest scores. All 40 participating students completed the posttest, and no cases were excluded because of missing outcome data. Given the posttest-only design and the study's specific instructional context, the results were interpreted as evidence of differences in observed posttest performance rather than direct evidence of individual improvement over time.

2.7 *Ethical Considerations*

Ethical procedures were considered throughout the research process to protect the rights, privacy, and well-being of the elementary-school students participating in the study. Before data collection, administrative research permission was obtained from the school principal and the local Kesatuan Bangsa dan Politik (Kesbangpol) authority. Written informed consent was obtained from the students' parents or legal guardians before their children participated in the research. In addition, students were informed about the research activities in language appropriate to their age and were asked to indicate their willingness to participate. Thus, student participation was based on their expressed willingness and parental or guardian consent. Confidentiality was maintained by replacing students' personal identities with codes or initials in research records and the reporting of findings. The collected data were used for academic and research purposes, and participants' personal information was protected from

disclosure. The instructional and assessment activities were conducted within the students' educational context, taking their age and learning conditions into consideration.

The study did not obtain formal approval from an institutional research ethics committee. This limitation is explicitly acknowledged to ensure transparency regarding the ethical review status of the research. Nevertheless, administrative permission, parental or guardian consent, student assent, and confidentiality procedures were implemented during the research process.

3. Result

3.1. Instrument Analysis

Before the main study, the initial 15-item mathematical critical-thinking test was pilot-tested on 14 participants to examine its psychometric quality. The analysis covered item validity, test reliability, item difficulty, and discrimination power. The results of these analyses were considered jointly to determine which items were sufficiently suitable for inclusion in the final posttest instrument.

The validity analysis was conducted for all 15 initial essay items. The results showed variations in the validity coefficients among the items. Most items demonstrated acceptable validity coefficients, whereas several items showed low validity or did not meet the predetermined validity criteria.

Table 2. Test Result for Validity Test Questions

Item	Validity Coefficient	Interpretation	Decision
1	0.420	Moderate validity	Excluded/Revision
2	0.575*	Moderate validity	Retained
3	0.578**	Moderate validity	Retained
4	0.817**	High validity	Retained
5	0.527*	Moderate validity	Retained
6	0.607*	Moderate validity	Retained
7	0.817**	High validity	Retained
8	0.644*	Moderate validity	Retained
9	0.566*	Moderate validity	Retained
10	NR	Not valid	Excluded
11	0.694**	Moderate validity	Retained
12	0.681**	Moderate validity	Retained
13	0.368	Low validity	Excluded/Revision
14	0.826**	High validity	Retained
15	0.257	Very low validity	Excluded

The item-validity analysis was conducted for all 15 initial essay items. The validity coefficients varied across the items, ranging from 0.257 to 0.826 among the items for which numerical coefficients were reported. Items 4, 7, and 14 showed high validity coefficients of 0.817, 0.817, and 0.826, respectively. Several other items showed moderate validity coefficients, including items 2, 3, 5, 6, 8, 9, 11, and 12. Items 13 and 15 showed lower validity coefficients of 0.368 and 0.257, respectively. Based on the item validity analysis and the overall instrument evaluation, 11 items were selected for use in the final posttest. Four items that did not meet the required criteria were excluded from the final instrument. The selected items were subsequently used to measure students' mathematical critical thinking skills in both the experimental and control groups.

The internal consistency analysis using Cronbach's Alpha produced a coefficient of 0.846 based on the pilot-test data from 14 participants. This value indicated a high level of internal consistency according to the classification adopted in this study. The result provided evidence that the test items demonstrated satisfactory internal consistency in the pilot testing. However, this coefficient represents internal consistency rather than agreement between independent scorers.

The difficulty analysis was conducted to examine the level of difficulty of the initial 15 essay items. The results indicated that the items varied in their difficulty levels, with most items falling within acceptable difficulty categories for the purpose of the study.

Table 3. Test Questions for Difficulty Level and Criteria

No. Item	Difficulty Index (P)	Difficulty Level	Criteria
1	0.72	Easy	0.71–1.00
2	0.65	Moderate	0.31–0.70
3	0.63	Moderate	0.31–0.70
4	0.60	Moderate	0.31–0.70
5	0.58	Moderate	0.31–0.70
6	0.56	Moderate	0.31–0.70
7	0.54	Moderate	0.31–0.70
8	0.52	Moderate	0.31–0.70
9	0.50	Moderate	0.31–0.70
10	0.75	Easy	0.71–1.00
11	0.45	Moderate	0.31–0.70
12	0.48	Moderate	0.31–0.70
13	0.78	Easy	0.71–1.00
14	0.68	Moderate	0.31–0.70
15	0.80	Easy	0.71–1.00

The difficulty level analysis was conducted to determine the extent to which each test item could be answered correctly by the students. The analysis used the difficulty index (P), with values ranging from 0.00 to 1.00, in which a higher value indicates that a greater proportion of students were able to answer the item correctly. Based on the criteria used in this study, The difficulty indices ranged from 0.45 to 0.80. Based on the criteria applied in this study, indices from 0.31 to 0.70 were classified as moderate, whereas indices from 0.71 to 1.00 were classified as easy. Eleven items (Items 2–9, 11, 12, and 14) fell within the moderate category, with indices ranging from 0.45 to 0.68. The remaining four items (Items 1, 10, 13, and 15) were categorized as easy, with indices ranging from 0.72 to 0.80. The distribution indicates that the test contained a greater proportion of moderately difficult items, providing variation in item difficulty for assessing students' mathematical critical-thinking performance.

The discrimination analysis was conducted to determine the ability of each item to distinguish between students with different levels of mathematical ability. The results indicated that most items demonstrated acceptable discrimination power, whereas several items showed weak discrimination and were excluded from the final instrument.

Table 4. Test Questions for Discrimination Power and Criteria

Number	Distinguishing Feature	Criteria
1	0.302	Excluded
2	0.492	Question item accepted/good

Number	Distinguishing Feature	Criteria
3	0.492	Question item accepted/good
4	0.804	Question item accepted/good
5	0.442	Question item accepted/good
6	0.601	Question item accepted/good
7	0.804	Question item accepted/good
8	0.547	Question item accepted/good
9	0.470	Question item accepted/good
10	0.000	excluded
11	0.618	Question item accepted/good
12	0.554	Question item accepted/good
13	0.214	Excluded
14	0.739	Question item accepted/good
15	0.141	Excluded

The discrimination indices ranged from 0.000 to 0.804. Eleven items demonstrated acceptable or good discrimination, with coefficients ranging from 0.442 to 0.804. These items were Items 2–9, 11, 12, and 14. In contrast, Items 1, 10, 13, and 15 had discrimination indices of 0.302, 0.000, 0.214, and 0.141, respectively, and were excluded because their ability to distinguish between students with different levels of mathematical performance was considered insufficient.

The final selection was based on the combined evidence from the four item-analysis components rather than on a single statistical criterion. Items 2–9, 11, 12, and 14 were retained because they demonstrated moderate difficulty, acceptable or good discrimination, and validity results considered adequate for the instrument. Conversely, Items 1, 10, 13, and 15 were excluded because they were classified as easy and demonstrated weak discrimination. Their validity results also provided additional grounds for exclusion, particularly for Items 10, 13, and 15. Although Item 1 showed a moderate validity coefficient, its relatively weak discrimination and easy difficulty level did not support its retention. Accordingly, the final instrument consisted of 11 essay items, with a maximum raw score of 176. The same final instrument was administered to both the experimental and control groups after the instructional intervention.

3.2. Implementation Fidelity of the PjBL Intervention

The classroom observation results indicated that the planned instructional activities were implemented at a very high level. The average implementation score across the three observed aspects was 97.1%, categorized as *Very Well Implemented*. Specifically, the model syntax aspect achieved 97.2%, the social system aspect reached 96.4%, and the reaction principles aspect obtained 97.8%. These results indicate that the observed implementation of the instructional model was consistently high across all three aspects.

Tabel 5. Implementation Fidelity of the PjBL Intervention

Observed aspect	Implementation (%)	Category
Model syntax	97.2	Very Well Implemented
Social system	96.4	Very Well Implemented
Reaction principles	97.8	Very Well Implemented
Average	97.1	Very Well Implemented

The observation findings provide supplementary evidence regarding the implementation of the planned learning activities and help contextualize the interpretation of the posttest results. However, the observation scores represent evidence of implementation and should not, by themselves, be interpreted as evidence of the effectiveness of PjBL in improving students' mathematical critical-thinking skills.

3.3. Descriptive Results of Mathematical Critical Thinking Skills

The posttest was administered to both the experimental and control groups after the completion of the learning intervention. The experimental group consisted of 20 elementary school students who received mathematics instruction through Project-Based Learning, whereas the control group consisted of 20 students who received conventional mathematics instruction. The descriptive results of students' mathematical critical thinking skills are presented in Table 6.

Table 6. Descriptive Statistics of Mathematical Critical-Thinking Posttest Scores

Group	n	Mean	SD	Minimum	Maximum
Experimental	20	90.00	2.68	84	95
Control	20	64.60	5.56	53	72

As presented in Table 5, the experimental group obtained a mean score of 90.00 (*SD* = 2.68), whereas the control group obtained a mean score of 64.60 (*SD* = 5.56). The observed mean difference was 25.40 points in favor of the experimental group. The experimental group's scores ranged from 84 to 95, while the control group's scores ranged from 53 to 72. The results of the normality and homogeneity tests are presented in the following subsections.

A normality test was conducted before hypothesis testing to examine the distribution of posttest scores in both groups. The Shapiro-Wilk test was performed using IBM SPSS Statistics version 27. The results of the normality test are presented in Table 7.

Table 7. Shapiro–Wilk Test of Normality for Mathematical Critical-Thinking Scores

Group	n	W	p	Interpretation
Experimental Group	20	.984	.976	Normal
Control Group	20	.957	.488	Normal

The normality of the mathematical critical-thinking posttest scores was examined separately for the experimental and control groups using the Shapiro–Wilk test. As shown in Table 7, the experimental group obtained a Shapiro–Wilk statistic of $W = .984$ ($p = .976$), while the control group obtained $W = .957$ ($p = .488$). Both p-values exceeded the .05 significance level, indicating that the tests did not provide statistically significant evidence of departures from normality in either group. Accordingly, the normality assumption was considered acceptable for the subsequent comparison of group means. Because the homogeneity-of-variance assumption was not satisfied, Welch's independent-samples t-test was used for the inferential analysis. The homogeneity of variance test was conducted using Levene's test to determine whether the variances of the posttest scores were equal between the experimental and control groups. The results are presented in Table 8.

Table 8. Levene's Test of Homogeneity of Variance

Variable	Levene's F	df1	df2	p	Interpretation
Mathematical critical-thinking scores	9.855	1	38	.003	Variances are unequal

The results indicated a statistically significant difference in group variances, $F(1, 38) = 9.855$, $p = .003$. Because the p-value was below the .05 significance level, the assumption of equal variances was not satisfied. Therefore, Welch's independent-samples t-test was used to compare the mean posttest scores between the two groups because this procedure accommodates unequal variances. The use of Welch's test ensured that the inferential comparison did not rely on the assumption of variance homogeneity.

3.4. Hypothesis Testing

The research hypothesis was tested using Welch's independent-samples t-test to examine whether a statistically significant difference existed in mathematical critical-thinking posttest scores between students in the Project-Based Learning (PjBL) group and those in the conventional-instruction group. This test was selected because the normality assumption was considered acceptable, whereas Levene's test indicated that the equal-variance assumption was not satisfied. The significance level was set at .05. The null hypothesis (H_0) stated that there was no difference in mean posttest scores between the two groups, while the alternative hypothesis (H_1) stated that a difference existed.

Table 9. Independent-Samples Test (Welch's t-Test)

Statistic	Value
t	18.42
Degrees of freedom (df)	27.36
Sig. (2-tailed)	< .001
Mean difference	25.40
95% CI of the difference — Lower	22.57
95% CI of the difference — Upper	28.23
Hedges' g	5.71

As presented in Table 9, Welch's independent-samples t-test indicated a statistically significant difference in mathematical critical-thinking posttest scores between the experimental and control groups, $t(27.36) = 18.42$, $p < .001$. The estimated mean difference was 25.40 points, with a 95% confidence interval ranging from 22.57 to 28.23 points. Therefore, the null hypothesis was rejected. The reported Hedges' g of 5.71 suggests a very large standardized difference between the groups.

These findings indicate that students who participated in PjBL obtained higher observed mathematical critical-thinking posttest scores than students who received conventional instruction. However, the study involved two instructional groups formed from students within a single classroom, rather than two independently selected intact classes. Although the initial diagnostic scores were used to distribute students alternately between the groups with the aim of achieving relatively balanced initial mathematical proficiency, the allocation did not involve individual random assignment. Furthermore, the two groups were taught by different teachers and at different times, introducing potential instructor-related and scheduling influences. Consequently, the observed difference cannot be attributed exclusively to the instructional approach. These methodological considerations should be taken into

account when interpreting the findings and limit the strength of causal conclusions that can be drawn from the study.

4. Discussion

The findings of this study indicate a statistically significant difference in mathematical critical-thinking performance between elementary students who participated in Project-Based Learning (PjBL) and those who received conventional mathematics instruction. The PjBL group achieved a higher mean posttest score (M = 90.0) than the control group (M = 64.6), with a mean difference of 25.40 points. Welch's independent-samples t-test confirmed that this difference was statistically significant, $t(27.36) = 18.42$, $p < .001$, with a very large effect size (Hedges' g = 5.71). These results suggest that, in the instructional context examined, participation in PjBL was associated with substantially higher observed mathematical critical-thinking performance than conventional instruction. This finding is consistent with previous research indicating that PjBL can be associated with positive learning outcomes and the development of higher-order thinking skills, although the reported outcomes and magnitude of effects vary across educational settings and implementation approaches [38], [40]. Research in primary mathematics education has also highlighted the potential of project-based activities to support mathematical thinking and problem-solving [43], while systematic evidence has identified critical thinking as an important outcome examined in elementary PjBL research [45]. The present results should nevertheless be interpreted as a difference in posttest performance rather than direct evidence of individual improvement, because students' mathematical critical thinking was not measured before the intervention.

The present finding is consistent with, but also extends, previous research on Project-Based Learning in elementary education. Previous systematic evidence has generally reported positive associations between PjBL and students' learning outcomes, although the reported effects vary according to educational level, instructional implementation, and outcome measures [38], [40]. In primary mathematics education, Rehman et al. [43] reported that mathematics project-based learning can support the development of twenty-first-century skills, particularly through learning activities that require students to engage with mathematical problems and apply mathematical knowledge in meaningful contexts. However, research on PjBL in elementary mathematics has also examined outcomes such as mathematical problem-solving and creative thinking rather than focusing specifically on mathematical critical-thinking performance [46]. A recent systematic review further indicates that critical thinking has emerged as an important outcome in elementary PjBL research, but substantial variation remains in project characteristics, instructional support, and assessment approaches across studies [45]. The present study therefore contributes to this body of evidence by providing a focused empirical comparison of mathematical critical-thinking performance between students participating in PjBL and those receiving conventional mathematics instruction, without incorporating additional technological, interdisciplinary, or culturally specific components into the instructional intervention.

One possible explanation for the higher mathematical critical-thinking performance observed in the PjBL group is the cognitively demanding structure of project-based activities. Unlike instructional activities that primarily emphasize the acquisition and reproduction of mathematical procedures, PjBL requires students to engage with questions or problems, investigate relevant information, consider alternative solutions, make decisions, and

communicate the results of their work (Mufadilah et al., 2025) (Mufadilah et al., 2025) . These activities create opportunities for students to practice cognitive processes that are closely related to critical thinking, including analyzing information, evaluating possible solutions, providing justification, and drawing conclusions (Susanto et al., 2021) . This interpretation is consistent with meta-analytic evidence showing that PjBL is associated with higher critical-thinking performance than more traditional instructional approaches, although the magnitude of the association varies across educational levels and comparison conditions [38], (Tafakur et al., 2023). In mathematics education, project-based activities may be particularly relevant because students are required not only to obtain mathematically correct answers but also to explain relationships, interpret information, and justify the reasoning underlying their solutions [43]. Thus, the higher performance observed in the present study may be interpreted in relation to the opportunities that the PjBL learning environment provides for students to engage in inquiry-oriented and cognitively demanding mathematical activities, rather than as evidence that any single PjBL component independently produced the observed difference.

The mathematical context of project-based learning may provide an additional explanation for the observed difference in students' critical-thinking performance. In mathematics, projects can situate abstract concepts within meaningful situations that require students to interpret information, identify relevant mathematical relationships, select appropriate representations or procedures, and explain the reasoning underlying their solutions. Such activities can move students beyond the reproduction of mathematical procedures toward the interpretation and application of mathematical ideas in context (Ismael et al., 2026) (Darwis et al., 2024; Rossi et al., 2021) . This interpretation is supported by research on mathematics project-based learning at the primary level, which reported significant differences in students' critical-thinking performance between project-based and traditional instructional conditions [43]. Similar evidence from elementary mathematics research suggests that learning activities involving meaningful or contextual mathematical problems can provide opportunities for students to analyze information and formulate logical reasoning when solving mathematical tasks (Ahdhianto et al., 2020) . In the present study, therefore, the use of project-oriented mathematics activities may have created learning situations in which students were required to connect mathematical representations with the problem context, potentially supporting the higher level of critical-thinking performance observed in the PjBL group.

Another aspect that may help explain the observed difference is the opportunity for students to participate more actively in learning and to make decisions during project activities. PjBL generally positions students as active participants who are involved in planning, investigating, developing solutions, and presenting project outcomes, rather than limiting their role to receiving and reproducing information. Such participation can create opportunities for students to monitor their progress, consider alternative approaches, and take greater responsibility for the mathematical decisions involved in completing a project. Previous research has identified student autonomy and active participation as important characteristics of project-based learning, while also emphasizing that autonomy needs to be accompanied by appropriate teacher scaffolding, particularly for younger learners [40]. A recent systematic review of PjBL in elementary education similarly reported that project-based activities can support students' critical-thinking development through active engagement in analyzing problems, making decisions, and constructing solutions [45]. In the present study,

therefore, the higher critical-thinking performance observed in the PjBL group may be partly interpreted in relation to the greater opportunities for active participation and decision-making provided by the instructional structure, although autonomy and engagement were not independently measured as explanatory variables.

Collaborative interaction represents another characteristic of PjBL that may be relevant to the development of students' mathematical critical-thinking performance. Project activities commonly require students to exchange ideas, compare alternative solutions, explain their reasoning, and respond to the perspectives of their peers. Such interactions can create opportunities for students to articulate mathematical arguments and reconsider their initial interpretations when confronted with alternative explanations. Evidence from systematic reviews of PjBL in elementary education indicates that project-based activities can support collaboration and communication alongside critical-thinking development [45], while reviews of PjBL in mathematics education have similarly identified collaborative project work as a recurring feature of project implementation [43]. From a mathematical perspective, explaining and negotiating solutions with peers may encourage students to make their reasoning more explicit and to examine whether their arguments are supported by appropriate mathematical evidence. In the present study, this collaborative dimension may therefore provide a plausible pedagogical context for the higher critical-thinking performance observed in the PjBL group, although the contribution of peer collaboration itself was not separately measured or tested.

The role of teacher scaffolding is particularly important when PjBL is implemented with elementary students, because younger learners may require structured guidance while gradually assuming responsibility for complex learning tasks. In a project-based mathematics classroom, scaffolding can include clarifying the problem, directing students toward relevant mathematical information, prompting them to explain their reasoning, providing feedback, and helping them evaluate the adequacy of their solutions without taking over the problem-solving process (Fitriadi et al., 2024; Masithoh et al., 2025) . Previous research has emphasized that teacher support, appropriate guidance, and students' preparation for collaborative work are important conditions for the successful implementation of PjBL, particularly in kindergarten and elementary education [40], [43]. Evidence from systematic reviews further indicates that the fidelity of PjBL interventions varies substantially across studies, especially in relation to the amount of teacher guidance, metacognitive support, assessment practices, and the degree of autonomy provided to students [40], [45]. These considerations are relevant to the present findings because the higher critical-thinking performance observed in the PjBL group should be interpreted not simply as a consequence of assigning students to projects, but in relation to how the project activities were structured and supported during instruction. Thus, effective PjBL implementation in elementary mathematics requires an appropriate balance between student independence and teacher scaffolding so that students can engage in cognitively demanding mathematical activities while receiving sufficient support to develop and communicate their reasoning.

From a pedagogical perspective, the findings suggest that project-based learning can provide a meaningful instructional structure for integrating mathematical content with higher-order cognitive activities in elementary classrooms. Rather than treating mathematical concepts primarily as procedures to be reproduced, project-oriented instruction can organize learning around situations in which students need to interpret information, apply

mathematical concepts, solve problems, justify their reasoning, and communicate their solutions. Previous research in mathematics education has reported that project-based learning is associated with diverse outcomes, including higher-order thinking, conceptual understanding, problem solving, creative thinking, and critical thinking [38], [43], [46], [49]. Systematic reviews of mathematics education further indicate that project-based approaches are commonly implemented through meaningful problems and authentic contexts that encourage students to connect mathematical knowledge with practical situations and to develop reasoning and communication skills [43], [47], [49]. For elementary mathematics instruction, these findings imply that the pedagogical value of PjBL lies not simply in assigning students a project, but in designing projects that maintain clear mathematical objectives while requiring students to reason about, represent, apply, and evaluate mathematical ideas. Accordingly, the present findings support the use of carefully designed project-oriented mathematics activities as one instructional option for creating opportunities for mathematical critical-thinking performance, while recognizing that the quality of the project design and its alignment with learning objectives remain essential.

For teachers, the findings highlight the importance of designing and facilitating PjBL in ways that preserve both the authenticity of the project and the mathematical objectives of instruction. Effective implementation requires teachers to formulate projects around meaningful mathematical questions, provide clear expectations for the learning outcomes, organize opportunities for students to investigate and discuss alternative solutions, and use formative feedback to guide students' reasoning throughout the project process [38], [40]. Previous studies and systematic reviews have emphasized that the effectiveness of PjBL depends not only on the presence of project activities but also on teacher guidance, instructional scaffolding, appropriate assessment, and students' preparation for collaborative work [40], [43], [45]. In mathematics education, teachers therefore need to ensure that project activities require students to use mathematical concepts, representations, reasoning, and problem-solving strategies rather than allowing the production of a project artifact to become the primary learning objective [43], [46], [49]. This consideration is particularly important in elementary classrooms, where students may require more explicit guidance to interpret mathematical problems, organize their work, evaluate their solutions, and communicate their reasoning [40], [45]. Accordingly, the present findings suggest that teachers may use PjBL as an instructional option for developing mathematical critical-thinking opportunities when project objectives, mathematical content, student activities, scaffolding, and assessment are deliberately aligned.

Several limitations should be considered when interpreting the findings of this study. First, the posttest-only quasi-experimental design allows the study to identify differences in mathematical critical-thinking performance between the PjBL and conventional-instruction groups, but it does not provide the same level of evidence for individual changes in students' performance over time as a pretest–posttest design would provide. Second, the participants were drawn from a specific elementary-school context and were involved in a particular mathematics learning topic and instructional setting; therefore, the findings should not be generalized beyond comparable populations and contexts without further evidence. Third, the study focused on mathematical critical-thinking performance as the principal outcome and did not independently measure potential explanatory processes such as student autonomy, collaboration, motivation, engagement, or metacognitive regulation. Consequently, the

discussion of these processes in relation to the observed differences should be understood as theoretically informed interpretation rather than as empirically tested mediation or causal mechanisms. Finally, although the study employed an essay-based assessment designed to capture mathematical critical-thinking performance, the interpretation of students' performance remains dependent on the characteristics of the assessment tasks and scoring procedures. These limitations indicate that the findings provide context-specific evidence regarding differences associated with PjBL, while broader conclusions concerning its long-term effects, underlying mechanisms, and generalizability require further investigation [38], [40], [45], [49].

Future research can extend the present findings by employing stronger longitudinal or pretest–posttest designs to examine changes in students' mathematical critical-thinking performance across the instructional period and by involving larger and more diverse samples from different elementary-school contexts. Such designs would provide a stronger basis for examining whether differences associated with PjBL remain consistent across students, schools, mathematical topics, and instructional conditions [38], [40], [43], [49]. Further studies should also consider measuring potential explanatory processes, such as student engagement, autonomy, collaboration, motivation, and metacognitive regulation, alongside mathematical critical thinking so that the relationships among instructional conditions, learning processes, and outcomes can be examined more directly [40], [45], [49]. In addition, future research could compare standard PjBL with PjBL incorporating specific technological, interdisciplinary, or culturally contextualized components to determine whether these additional features provide evidence of added value beyond project-based instruction itself [44], [47], [48]. Replication across different mathematical topics and grade levels, together with the use of multiple forms of critical-thinking assessment, would further strengthen the evidence concerning the consistency, transferability, and educational relevance of PjBL for elementary mathematics learning.

Taken together, the findings and the preceding discussion indicate that PjBL represents a promising instructional approach for creating opportunities for mathematical critical-thinking performance in elementary mathematics classrooms. Its potential value is not attributable simply to the use of projects, but to the way project activities can engage students in meaningful mathematical problems, inquiry, reasoning, decision-making, explanation, and evaluation while providing opportunities for active and collaborative participation [38], [43], [45], [49]. At the same time, the evidence discussed in this study indicates that these opportunities depend on appropriate project design, alignment with mathematical learning objectives, teacher scaffolding, and implementation quality, particularly when PjBL is used with younger learners [40], [43], [47]. The present study therefore contributes context-specific empirical evidence that students participating in PjBL demonstrated different posttest mathematical critical-thinking performance from students receiving conventional mathematics instruction, while the interpretation of this difference should remain bounded by the study design, participants, instructional context, and assessment conditions. Overall, the findings support continued empirical investigation of PjBL in elementary mathematics, particularly research that can clarify its effectiveness across contexts and identify the instructional conditions under which project-based learning is most consistently associated with meaningful mathematical critical-thinking development.

5. Conclusion

This study found a statistically significant difference in mathematical critical-thinking posttest performance between elementary students who participated in Project-Based Learning (PjBL) and those who received conventional mathematics instruction. The PjBL group achieved a higher mean score (M = 90.0) than the control group (M = 64.6), with a mean difference of 25.40 points. Welch's independent-samples t-test confirmed that the difference was statistically significant, $t(27.36) = 18.42$, $p < .001$, with a very large effect size (Hedges' g = 5.71). These findings suggest that PjBL may be a useful instructional option for elementary mathematics when project activities are aligned with mathematical learning objectives and supported by appropriate teacher guidance. The contribution of this study is its focused, context-specific comparison of mathematical critical-thinking performance under PjBL and conventional instruction. However, because the study employed a posttest-only quasi-experimental design in a specific educational context, the findings should not be interpreted as direct evidence of individual improvement or generalized uncritically to other populations and settings. Future research should employ pretest–posttest or longitudinal designs, involve more diverse samples, and examine different mathematical topics to assess the consistency and broader applicability of these findings.

Acknowledgments

The author would like to express sincere gratitude to Muhammadiyah University of Muara Bungo (UMMUBA) for its willingness to contribute to this research, enabling it to be completed successfully.

Daftar Pustaka

Abdul Halim, F. (2025). Project-Based Learning in the Independent Curriculum: Improving Secondary Students' Mathematical Problem-Solving Skills. EDUKASIA Jurnal Pendidikan Dan Pembelajaran, 6(2), 1027–1038. https://doi.org/10.62775/edukasia.v6i2.1676

Agustini, R., Meilanie, R. S. M., & Pujiastuti, S. I. (2024). Enhancing Critical Thinking and Curiosity in Early Childhood Through Inquiry-Based Science Learning. Aulad: Journal on Early Childhood, 7(3), 734–743. https://doi.org/10.31004/aulad.v7i3.780

Ahdhianto, E., Marsigit, Haryanto, & Nurfauzi, Y. (2020). Improving fifth-grade students' mathematical problem-solving and critical thinking skills using problem-based learning. Universal Journal of Educational Research, 8(5), 2012–2021. https://doi.org/10.13189/ujer.2020.080539

Almulla, Mohammed Abdullatif. (2020). The Effectiveness of the Project-Based Learning (PBL) Approach as a Way to Engage Students in Learning. Sage Open, 10(3), 2158244020938702. https://doi.org/10.1177/2158244020938702

Anchunda, H. Y., & Kaewurai, W. (2025). An instructional model development based on inquiry-based and problem-based approaches to enhance prospective teachers' teamwork and collaborative problem-solving competence. Social Sciences & Humanities Open, 11(6), 101480. https://doi.org/https://doi.org/10.1016/j.ssaho.2025.101480

Apriliandi, D. (2025). Efforts to Improve Students' Critical Thinking Skills in Mathematics Learning by Implementing the Discovery Learning Model in Elementary Schools. Journal of Indonesian Primary School, 2(4), 2025. https://journal.mgedukasia.or.id/index.php/jips

Aridanthy, V., Kusumah, Y. S., Dahlan, J. A., Prabawanto, S., & Melati, C. Y. (2026). How do students solve critical thinking tasks in trigonometry? A qualitative analysis of critical thinking skills. Indonesian Journal of Science and Mathematics Education, 9(1), 234–246. https://doi.org/10.24042/ijsme.v9i1.25867

Auliyani, C., Arianto, F., & Kholidya, C. (2025). A SYSTEMATIC LITERATURE REVIEW OF PROJECT-BASED LEARNING INTEGRATED WITH STEM EDUCATION: EXAMINING IMPLEMENTATION STRATEGIES, OUTCOMES, AND CHALLENGES. Jurnal Visi Ilmu Pendidikan, 17(1), 214–231. https://doi.org/10.26418/jvip.v17i1.85610

Basid, A., Sutrisno, E., & Aliyeva, L. (2024). Analysis of the Effect of Contextual Problem Solving on

Students' Mathematical Reasoning Ability. International Journal of Science and Mathematics Education, 1, 24–33. https://doi.org/10.62951/ijsme.v1i3.258

Dahal, P., & G.C., L. (2026). Effectiveness of Project-Based Learning in Enhancing Mathematical Reasoning and Creativity: A Systematic Review. KMC Journal, 8(1), 198–212. https://doi.org/10.3126/kmcj.v8i1.90657

Darwis, R., Alimuddin, & Patimbangi, A. (2024). Higher Order Thinking and Critical Thinking Skills in Problem-Based Learning Environments: A Systematic Review. Journal of Learning and Development Studies, 4, 21–33. https://doi.org/10.32996/jlds.2024.2.2.3

Dewi, Y., Khalid, A., & Agam, A. (2025). The Role of Critical Thinking Skills in Enhancing Problem-Solving Abilities among High School Students. Journal of Education and Social Science, 2(1), 19–24. https://doi.org/10.70716/jess.v2i1.191

Dinda Antika Putri, Sumarno, Berta Apriza, & Asri widianingrum. (2025). Analysis of the Effectiveness of Implementing Project-Based Learning Models on Students' Critical Thinking Skills in Elementary Schools: A Systematic Literature Review. Journal for Lesson and Learning Studies, 8(1), 129–142. https://doi.org/10.23887/jlls.v8i1.90392

Eshun, I., Koranteng, U., Ajayi, A., & Ogar, E. (2026). Effectiveness of Project-Based Learning in Developing Critical Thinking Skills. Journal of ICT and Education, 7(4), 10–21. https://doi.org/10.69739/jicte.v1i1.1619

Facione, P. (2015). Critical Thinking: What It Is and Why It Counts. Insight Assessment.

Fatahillah, A., & Faradillah, A. (2023). Project-based learning assisted augmented reality in increasing students' mathematical understanding of concepts. Jurnal Elemen, 9(2), 450–463. https://doi.org/10.29408/jel.v9i2.12703

Ferrero, M., Vadillo, M., & P. León, S. (2021). Is project-based learning effective among kindergarten and elementary students? A systematic review. PLOS ONE Journal, 16(4), e0249627. https://doi.org/10.1371/journal.pone.0249627

Fitri Yabashiru, Berta Apriza, & Karsoni Berta Dinata. (2025). Mathematics Learning Difficulties among Elementary School Students. Journal for Lesson and Learning Studies, 8(2), 304–315. https://doi.org/10.23887/jlls.v8i2.94756

Fitriadi, F., Herpratiwi, H., Yulianti, D., Setiyadi, A. G., Hariri, H., Sunyono, S., Haenilah, E., & Mukhlis, H. (2024). Enhancing critical thinking in elementary education: A systematic review of effective learning models. Multidisciplinary Reviews, 8(6), 2025157. https://doi.org/10.31893/multirev.2025157

Gradini, E., B, F., Noviani, J., & Ulya, K. (2025). Fostering Higher-Order Thinking Skills in Mathematics Education: Strategies, Challenges, and Classroom Practices. Prisma Sains : Jurnal Pengkajian Ilmu Dan Pembelajaran Matematika Dan IPA IKIP Mataram, 13(2), 135. https://doi.org/10.33394/j-ps.v13i2.15099

Hadi, S., Dolk, M., Kamaliyah, & Hidayanto, T. (2025). Mathematical reasoning: How students learn mathematics? Journal on Mathematics Education, 16(3), 937–954. https://doi.org/10.22342/jme.v16i3.pp937-954

Ismael, I., Li, S., Luo, X., & Ali, N. (2026). Why critical thinking rarely surfaces in EFL classrooms: insights from Egyptian higher education and implications for ESP. Frontiers in Education, Volume 11-2026. https://www.frontiersin.org/journals/education/articles/10.3389/feduc.2026.1808262

Isnani, T. (2023). Implementation of Project-Based Learning Approach in Improving Critical Thinking Skills of Elementary School Students. Jurnal Ar Ro'is Mandalika (Armada), 3(1), 47–55. https://doi.org/10.59613/armada.v3i1.2844

Izzati, N., & Suryadi, D. A. (2026). Exploring Students' Critical Thinking Skills and Mathematical Communication Skills in Solving Statistical Problems. MaPan : Jurnal Matematika Dan Pembelajaran, 14(1), 85–105. https://doi.org/10.24252/mapan.2026v14n1a5

Koedinger, K., Corbett, A., & Perfetti, C. (2012). The Knowledge-Learning-Instruction Framework: Bridging the Science-Practice Chasm to Enhance Robust Student Learning. Cognitive Science, 36, 757–798. https://doi.org/10.1111/j.1551-6709.2012.01245.x

Koskinen, R., & Pitkäniemi, H. (2022). Meaningful Learning in Mathematics: A Research Synthesis of Teaching Approaches. International Electronic Journal of Mathematics Education, 17(2), em0679.

https://doi.org/10.29333/iejme/11715

Listiana, D., Puspita, A., Setyowati, R., Istiq'faroh, N., & Gunansyah, G. (2025). Implementation of the Project-Based Learning Model to Enhance Collaborative Skills of Elementary School Students. Journal of Innovation and Research in Primary Education, 4(2), 179–186. https://doi.org/10.56916/jirpe.v4i2.1218

Malau, F., Noverica, S., & Mariani, A. (2025). Enhancing Students' Mathematical Critical Thinking through Problem-Based Learning Assisted by MATLAB: A Classroom Action Research Study. Jurnal Pendidikan, Media, Strategi, Dan Metode., 2(3), 149–159. https://doi.org/10.67507/jupen.v2i03.394

Manalu, S., Afrida, N., & Harahap, S. (2025). Higher Order Thinking Skills in Reading Questions of English Textbook for 10 th Grade High School Students. Invention: Journal Research and Education Studies, 6(1). https://pusdikra-publishing.com/index.php/jres

Masithoh, S., Widodo, W., & Mustaji. (2025). Profile of Critical Thinking Skills in Elementary School Students. Journal of Innovation and Research in Primary Education, 4, 929–937. https://doi.org/10.56916/jirpe.v4i3.1469

Mawardha, F. N., Sholikhah, O. H., Putri, U. W. N., & Alvarez, J. I. (2026). Numeration Ability as a Foundation for Elementary Students' Reflective Thinking: A Systematic Literature Review. Educative: Jurnal Ilmiah Pendidikan, 4(2), 201–211. https://doi.org/10.70437/educative.v4i2.2189

Mufadilah, S., Anggraini, H., & Haryono, S. (2025). Project-Based Learning to Improve Problem Solving Skills in Early Childhood. JURNAL RISET PENDIDIKAN DAN PENGAJARAN, 4(1), 101–111. https://doi.org/10.55047/jrpp.v4i1.980

Mukaromah, A., Ilham, M., & Arifin, Z. (2021). The Effectiveness of Project-Based Learning in Improving Students' Critical Thinking Skills. Print) Journal of English Language and Education, 10(4), 2025. https://doi.org/10.31004/jele.v10i4.1292

Mulyawati1, Y., Japar2, M., & Nurhasanah3, N. (n.d.). International Conference on Elementary Education Needs Analysis for Developing an E-Module to Enhance Critical Thinking in Elementary Social Studies Learning.

Mustamin, K., Wahdah, W., Intiardy, D., Jumrah, A., & Pattiasina, P. (2024). The Impact of Project-Based Learning on Students' Collaboration Skills in Secondary Schools. International Journal of Educational Research Excellence (IJERE), 3(2), 992–998. https://doi.org/10.55299/ijere.v3i2.740

Ndiung, S., & Menggo, S. (2024). Project-Based Learning in Fostering Creative Thinking and Mathematical Problem-Solving Skills: Evidence from Primary Education in Indonesia. International Journal of Learning, Teaching and Educational Research, 23(8), 289–308. https://doi.org/10.26803/ijlter.23.8.15

Nurkanti, M., Lubis, M., Cartono, C., Hudha, A., Mohd Shukri, A. A., & Yasundari, Y. (2025). Meta-Analysis of the Effectiveness of Project-Based Learning in College Biology Education for the Development of Higher-Order Thinking Skills. Educational Process International Journal, 18(1), 19. https://doi.org/10.22521/edupij.2025.18.463

Nurlaela, I., Laily Alindra, A., & Mustikaati, W. (2025). PENGARUH MODEL PROBLEM BASED LEARNING (PBL) BERBANTUAN MEDIA AUGMENTED REALITY TERHADAP PENINGKATAN KEMAMPUAN BERPIKIR KRITIS IPA SISWA SEKOLAH DASAR (Vol. 10).

Oktaviani, M., Dwihapsari, K., Islami, M., Dewi, N., Fadhilah, R., & Palupi, Z. (2023). Cognitive Development of Elementary School Children in Developing Critical Thinking Ability and Understanding Mathematical Concepts. International Education Trend Issues, 1, 134–142. https://doi.org/10.56442/ieti.v1i3.178

Osborne, M. (2021). Teacher Instructional Practices and Student Mathematics Achievement. Journal of Educational Research and Practice, 11. https://doi.org/10.5590/JERAP.2021.11.1.25

Payaseunara, M., Helvia Riany, I., & Besar, A. (2025). Efforts to Improve Students' Logical Thinking Skills by Applying the Problem-Based Learning Model to Mathematics Learning at MIN Payaseunara. DEEP LEARNING: Journal of Educational Research, 1(4). https://ejournal.mgedukasia.or.id/index.php/deeplearning

Prasetyo, O., Silvita, Rina Oktaviana, Ulya Ruwaida, & Zevira Fransisca Aurora. (2026). From

Knowledge Acquisition to Competency Development: A Systematic Review of Deep Learning Approaches in Science Education. Indonesian Journal of Educational Research and Review, 9(1), 190–203. https://doi.org/10.23887/ijerr.v9i1.102658

Prastiti, T. D., Mairing, J. P., Sambada, D., & Ahmadah, I. F. (2026). PjBL–STEM learning design for enhancing mathematical critical thinking and environmental literacy through plastic waste recycling in elementary school. Glosains: Jurnal Sains Global Indonesia, 7(2), 78–102. https://doi.org/https://doi.org/10.59784/glosains.v7i2.719

Purnamasari, E., Waluya, S., Agoestanto, A., & Pujiastuti, E. (2026). Mathematical Critical Thinking in Trigonometry Under E-Module-Supported Project-Based Learning: An Explanatory Sequential Study Across Self-Reported Modality Preferences. International Journal of Environment, Engineering and Education, 8(3), 500–524. https://doi.org/10.55151/ijeedu.v8i3.566

Rehman, N., Huang, X., Batool, S., Andleeb, I., & Mahmood, A. (2024). Assessing the Effectiveness of Project-Based Learning: A Comprehensive Meta-Analysis of Student Achievement between 2010 and 2023. ASR: Chiang Mai University Journal of Social Sciences and Humanities, 11. https://doi.org/10.12982/CMUJASR.2024.015

Rehman, N., Zhang, W., Mahmood, A., Fareed, M. Z., & Batool, S. (2023). Fostering twenty-first century skills among primary school students through math project-based learning. Humanities and Social Sciences Communications, 10(1), 424. https://doi.org/10.1057/s41599-023-01914-5

Rossi, I. V., de Lima, J. D., Sabatke, B., Nunes, M. A. F., Ramirez, G. E., & Ramirez, M. I. (2021). Active learning tools improve the learning outcomes, scientific attitude, and critical thinking in higher education: Experiences in an online course during the COVID-19 pandemic. Biochemistry and Molecular Biology Education, 49(6), 888–903. https://doi.org/10.1002/bmb.21574

Shoffa, S., Kristanti, F., & Damayanti, A. (2026). Fostering Mathematical Creative Thinking Through the DOCAR Instructional Model: An Embedded Mixed-Methods Investigation Across Mathematical Self-Efficacy Levels. Journal of Education and Teaching (JET), 7(2), 683–705. https://doi.org/10.51454/jet.v7i2.855

Susanto, A., Zaenuri, Z., & Dewi, N. R. (2021). Students' Mathematical Critical Thinking Ability with Project Based Learning (PjBL) Model Based on Local Culture. Journal of Primary Education, 10(4), 485–496. https://doi.org/https://doi.org/10.15294/jpe.v10i4.55932

Tafakur, T., Retnawati, H., & Shukri, A. A. M. (2023). Effectiveness of project-based learning for enhancing students critical thinking skills: A meta-analysis. JINoP (Jurnal Inovasi Pembelajaran), 9(2), 191–209. https://doi.org/10.22219/jinop.v9i2.22142

Wahyuningrum, E., Bonyah, E., Yumiati, Y., Kartono, K., & Wijayanti, N. (2024). Exploring the relationship between problem-solving ability and mathematical disposition in 10-11 year's old students using model-eliciting activities. Al-Jabar : Jurnal Pendidikan Matematika, 15(2), 333–347. https://doi.org/10.24042/ajpm.v15i2.23765

Yusri, R., Yusof, A. M., & Sharina, A. (2024). A systematic literature review of project-based learning: research trends, methods, elements, and frameworks. International Journal of Evaluation and Research in Education, 13(5), 3345–3359. https://doi.org/10.11591/ijere.v13i5.27875