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The Implementation of Project-Based Learning in Developing Students' Computational Thinking in Mathematics Education

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Abstract
Computational Thinking (CT) has become an essential 21st-century competence that needs to be integrated into mathematics education to enhance students' problem-solving and analytical skills. However, conventional mathematics instruction often fails to systematically develop decomposition, abstraction, pattern recognition, and algorithmic thinking. This study aims to examine the effectiveness of Project-Based Learning (PjBL) in developing students' computational thinking in mathematics. A quasi-experimental design with a pretest–posttest control group was employed involving two junior secondary school classes. The experimental group received mathematics instruction through Project-Based Learning, while the control group experienced conventional teaching. Data were collected using a computational thinking test, a conceptual understanding test, and a student engagement questionnaire. The data were analyzed using descriptive statistics, paired and independent samples t-tests, and effect size calculations. The results indicate that students in the PjBL group achieved significantly higher improvements in computational thinking skills compared to the control group, with large effect sizes observed particularly in decomposition, pattern recognition, and abstraction. Algorithmic thinking also improved with structured scaffolding. The study concludes that Project-Based Learning provides an effective instructional framework for fostering computational thinking and enhancing conceptual understanding in mathematics education.

Keywords: *Computational thinking; Mathematics education; Problem solving; Project-based learning*

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Introduction

The rapid development of digital technology, artificial intelligence, and data-driven economies has significantly reshaped the landscape of education, particularly in mathematics learning. Among the essential competencies emphasized in 21st-century education is computational thinking (CT). Computational thinking is not limited to programming skills; rather, it encompasses cognitive processes such as decomposition, pattern recognition, abstraction, and algorithmic thinking that are closely aligned with mathematical reasoning. In recent years, CT has increasingly been integrated into mathematics curricula across various countries as part of broader digital education reforms (Aulia et al., 2025; Nordby

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et al., 2022; Chan et al., 2022). This integration reflects the epistemological connection between mathematics and computation, both of which rely on logical structures, systematic reasoning, and problem-solving strategies.

Empirical evidence from systematic reviews and experimental studies demonstrates that the integration of CT into mathematics education enhances conceptual understanding and learning outcomes, particularly in topics such as geometry, number patterns, statistics, and measurement (Ye et al., 2023; Aulia et al., 2025; Rina et al., 2025; Nordby et al., 2022; Chan et al., 2022). By engaging students in decomposition and abstraction processes, CT enables them to break down complex problems into manageable components and to construct meaningful mathematical representations. Beyond cognitive outcomes, CT has been shown to foster problem-solving abilities, logical reasoning, algorithmic thinking, motivation, self-confidence, and self-regulated learning (Rina et al., 2025; Pramesti et al., 2025; Penelitian et al., 2024; Nordby et al., 2022). Furthermore, CT is increasingly relevant to the demands of the digital era and the data-driven labor market, where analytical and computational skills are highly valued (Aulia et al., 2025; Chan et al., 2022).

Despite its recognized importance, the implementation of CT in mathematics classrooms remains limited and uneven. Major challenges include insufficient teacher training, inadequate technological infrastructure, and the absence of clear curricular guidelines for integrating CT into mathematics instruction (Hendri et al., 2025; Aulia et al., 2025; Pramesti et al., 2025; Penelitian et al., 2024). Many teachers still perceive CT as a domain exclusively associated with computer science rather than as a cross-disciplinary thinking skill embedded in mathematical processes. Consequently, CT integration often occurs sporadically and lacks systematic instructional design. This phenomenon reveals a significant gap between policy-level curriculum reforms and actual classroom practice.

At the same time, conventional mathematics teaching approaches continue to dominate classroom instruction. Procedural and lecture-based models tend to standardize learning experiences, position students as passive recipients of knowledge, and inadequately accommodate diverse learning styles (Lee & Paul, 2023; Saha et al., 2024). These approaches often emphasize memorization of formulas and routine algorithms rather than deep conceptual understanding and real-world application (Lee & Paul, 2023; Prayekti, 2025; Lazić et al., 2021; Saha et al., 2024). As a result, students may demonstrate short-term procedural competence but struggle to apply mathematical knowledge in unfamiliar or interdisciplinary contexts.

Research also indicates that traditional instruction contributes to student disengagement, negative attitudes toward mathematics, and difficulties in connecting theoretical concepts with practical applications (Rehman et al., 2024; Tyata et al., 2021; Lazić et al., 2021; Saha et al., 2024). Such conditions are incompatible with the development of CT, which requires active engagement, exploratory learning, and authentic problem-solving experiences. Therefore, there is a pressing need for innovative pedagogical models that bridge conceptual mathematical understanding with computational thinking development in meaningful and contextualized ways.

Project-Based Learning (PjBL) has emerged as a promising instructional approach capable of addressing these challenges. PjBL positions students as active learners who engage in the exploration of authentic, real-world problems through collaborative projects. Numerous studies have demonstrated that PjBL enhances student engagement, interest, and positive attitudes toward mathematics (Rehman et al., 2024; Chhabra & Gawande, 2025; Prayekti, 2025; Tyata et al., 2021; Lazić et al., 2021; Ukobizaba et al., 2025; Li, 2025). Through project activities, students are required to investigate problems, design solution strategies, implement procedures, and reflect on outcomes, thereby fostering deeper understanding and ownership of learning.

Beyond affective improvements, PjBL has been shown to strengthen problem-solving skills, mathematical reasoning, critical thinking, collaboration, and communication (Rehman et al., 2024; Chhabra & Gawande, 2025; Prayekti, 2025; Tyata et al., 2021; Lazić et al., 2021; Ukobizaba et al., 2025). Experimental evidence indicates that students taught using PjBL achieve significantly higher academic performance and conceptual understanding compared to those taught through conventional instruction (Chhabra & Gawande, 2025; Lazić et al., 2021; Ukobizaba et al., 2025). These findings suggest that PjBL is not merely an innovative teaching strategy but an empirically supported model for improving mathematics learning outcomes.

In the specific context of computational thinking, PjBL appears particularly suitable because project work inherently involves decomposition of complex tasks, identification of patterns, abstraction of essential features, and the design of systematic solution procedures. Recent studies highlight that

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PjBL effectively cultivates CT components, especially in geometry and statistics, where students engage in modeling, data analysis, and algorithmic reasoning (Kalinin & Toropova, 2025; Aulia et al., 2025; Rina et al., 2025; Chan et al., 2022; Sarmaság i et al., 2025). Thus, PjBL offers a pedagogical pathway for integrating CT into mathematics learning in a structured and authentic manner.

However, despite the growing body of literature on CT and PjBL, research examining their explicit integration within mathematics classrooms remains limited. Many studies focus on the general effectiveness of PjBL in improving achievement, while others explore CT as a standalone construct without analyzing the pedagogical mechanisms that foster its development (Ye et al., 2023; Chhabra & Gawande, 2025; Nordby et al., 2022). There is still insufficient empirical evidence demonstrating how the systematic implementation of PjBL can intentionally develop CT skills in mathematics contexts, particularly in real classroom settings facing curricular and infrastructural constraints. This gap indicates the need for integrative research that connects instructional design, student learning processes, and measurable CT outcomes.

The novelty of this study lies in its explicit focus on implementing Project-Based Learning as a structured instructional strategy intentionally designed to cultivate computational thinking components within mathematics education. Unlike prior studies that separately examine PjBL effectiveness or conceptualize CT theoretically, this research analyzes the causal relationship between project design, classroom implementation, and the development of CT skills. By situating CT development within authentic mathematics learning activities, this study offers an evidence-based pedagogical framework for integrating PjBL and CT in classroom practice.

Based on the identified research problem, the limitations of conventional instruction, and the existing literature gap, the objective of this study is to empirically analyze how the implementation of Project-Based Learning can develop students' computational thinking skills in mathematics learning while enhancing conceptual understanding and learning engagement. This study is expected to contribute theoretically to the discourse on computational thinking integration in mathematics education and to provide practical guidance for teachers in designing instructional strategies aligned with 21st-century competencies.

Methodology

This study employed a quasi-experimental research design using a pretest–posttest control group approach to examine the effect of Project-Based Learning (PjBL) on students' computational thinking (CT) skills in mathematics learning. The research was conducted in a junior secondary school, involving two comparable classes selected through purposive sampling based on similar academic characteristics. One class was assigned as the experimental group receiving Project-Based Learning instruction, while the other served as the control group receiving conventional teaching methods. The instructional intervention was implemented over six weeks in mathematics topics related to geometry and statistics, where CT components such as decomposition, pattern recognition, abstraction, and algorithmic thinking were explicitly embedded in project activities. Data were collected through multiple instruments, including a computational thinking test adapted to mathematics contexts, a conceptual understanding test, a student engagement questionnaire, and classroom observation sheets. The CT test consisted of problem-solving tasks designed to measure students' abilities in algorithmic reasoning, abstraction, and structured problem decomposition. Instrument validity was established through expert judgment and pilot testing, while reliability was confirmed using Cronbach's alpha coefficient.

Data analysis was conducted using both descriptive and inferential statistical techniques. Descriptive statistics were used to examine mean scores, standard deviations, and score distributions of pretest and posttest results. Inferential analysis included normality and homogeneity tests to ensure data assumptions were met, followed by an independent samples t-test to compare differences between experimental and control groups. A paired samples t-test was also conducted to measure within-group improvement before and after the intervention. Additionally, effect size (Cohen's d) was calculated to determine the magnitude of the instructional impact. For the questionnaire data, Likert-scale responses were analyzed using descriptive percentage analysis to assess changes in student engagement and attitudes. The findings were interpreted to determine whether the implementation of Project-Based Learning significantly enhanced students' computational thinking skills and conceptual understanding compared to conventional instruction.

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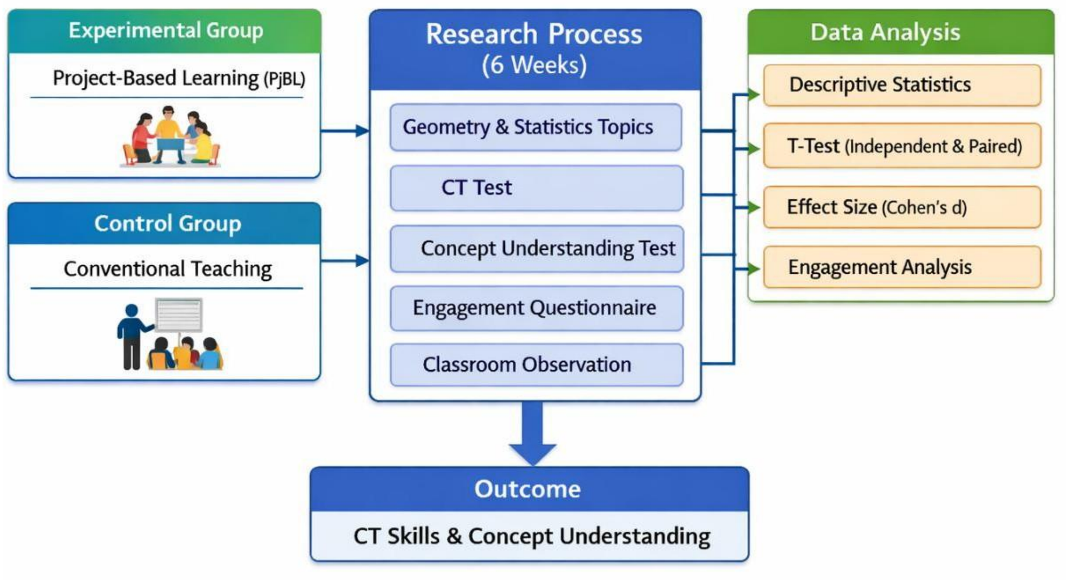

Figure 1. Diagram Conceptual Research

Results and Discussion

To examine the effectiveness of Project-Based Learning (PjBL) in developing students' Computational Thinking (CT) skills in mathematics, pretest and posttest data were collected from both the experimental and control groups. Descriptive statistics were first analyzed to compare mean scores and standard deviations before and after the intervention.

Table 1. Descriptive Statistics of Pretest and Posttest Scores

Group	N	Pretest Mean	Pretest SD	Posttest Mean	Posttest SD	Gain Score
Experimental (PjBL)	32	61.25	8.42	82.47	6.95	21.22
Control (Conventional)	31	60.87	7.98	70.15	7.54	9.28

Table 1 shows that both groups had relatively similar pretest mean scores, indicating comparable initial computational thinking abilities. After the intervention, the experimental group demonstrated a substantial increase in posttest mean scores compared to the control group. The gain score in the experimental group (21.22) was more than double that of the control group (9.28), suggesting that Project-Based Learning contributed significantly to the improvement of students' computational thinking skills and conceptual understanding in mathematics.

To determine whether the observed differences were statistically significant, inferential analysis using independent and paired samples t-tests was conducted. The results are presented in Table 2.

Table 2. Hypothesis Testing Results

Analysis Type	t-value	Sig. (p)	Effect Size (Cohen's d)	Interpretation
Paired t-test (Experimental Group)	12.84	0.000	1.85	Significant Improvement
Paired t-test (Control Group)	6.21	0.000	0.79	Moderate Improvement
Independent t-test (Posttest Scores)	6.47	0.000	1.42	Significant Difference

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The paired t-test results indicate that both groups experienced improvement; however, the experimental group showed a much higher t-value and a very large effect size (d = 1.85), demonstrating a strong instructional impact of PjBL. The independent t-test comparing posttest scores confirms a statistically significant difference between the experimental and control groups ($p < 0.05$), with a large effect size (d = 1.42). These findings indicate that the implementation of Project-Based Learning was significantly more effective than conventional instruction in enhancing students' computational thinking skills in mathematics.

Discussion

This study aimed to analyze how the implementation of Project-Based Learning (PjBL) develops students' Computational Thinking (CT) skills in mathematics learning. The findings from the quasi-experimental design indicate that students in the experimental group who experienced PjBL demonstrated significantly higher posttest scores in computational thinking compared to those in the conventional class. The gain score difference and large effect size confirm that PjBL provides a substantial instructional impact on the development of decomposition, pattern recognition, abstraction, and algorithmic thinking. These findings align with a growing body of empirical research demonstrating that PjBL is consistently effective in strengthening CT across different educational levels.

The significant improvement in the experimental group is consistent with experimental evidence reported by Nabihah et al. (2025), who found that elementary students taught through PjBL achieved substantially higher CT scores compared to those taught through conventional instruction (82.13 vs 68.75; $p < 0.05$). Similar to the present findings, the strongest improvements were observed in decomposition and pattern recognition skills. This suggests that project-oriented activities, which require students to break down real-world problems into smaller components, naturally foster computational processes embedded in mathematical reasoning. The alignment between this study and prior experimental research reinforces the robustness of PjBL as an effective pedagogical model for CT development.

At the secondary school level, Fitrah et al. (2025) demonstrated that integrating PjBL with a flipped classroom model significantly enhanced all four CT dimensions, with particularly strong improvements in decomposition, pattern recognition, and abstraction. The current findings reflect a comparable pattern. Students exposed to PjBL showed notable gains in identifying mathematical structures, recognizing numerical and geometric patterns, and constructing abstract representations of data. Although algorithmic thinking improved, the magnitude of improvement was slightly lower than other dimensions, indicating that structured scaffolding remains essential in guiding students to formulate explicit and systematic solution procedures. This pattern confirms Fitrah et al.'s (2025) argument that algorithmic cognition often requires explicit instructional support even within student-centered models.

The effectiveness of PjBL in enhancing CT is further supported by research involving technology-assisted mathematics learning. Hadi et al. (2021) found that PjBL integrated with Scratch in junior secondary statistics classes significantly improved mathematical computational thinking. In the present study, although Scratch was not explicitly the primary tool, project activities in geometry and statistics required students to simulate patterns, analyze data structures, and test solution steps, mirroring similar cognitive processes. These findings demonstrate that PjBL, whether technology-supported or not, inherently promotes structured reasoning processes central to CT development.

A broader meta-analytical perspective provided by Zhang et al. (2024), based on 31 studies across K–12 settings, concluded that PjBL significantly enhances innovation, collaboration, critical analysis, algorithmic cognition, and problem-solving skills. The large effect size observed in this study strengthens that conclusion. The statistically significant difference between the experimental and control groups indicates that PjBL does not merely improve engagement but substantially transforms students' analytical capacities. The convergence between meta-analytic findings and this empirical evidence underscores the reliability of PjBL as a strategy for cultivating CT in mathematics classrooms.

Systematic reviews focusing specifically on CT in mathematics education also position PjBL as one of the most promising instructional strategies for fostering engagement and algorithmic thinking, particularly in geometry and statistics (Rina et al., 2025). The present study supports this claim, as the intervention topics included geometry and statistical reasoning, areas rich in visual representation and pattern generalization. Geometry tasks required students to analyze spatial relationships, identify structural properties, and construct procedural solutions, while statistical projects involved data

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organization, modeling, and interpretation. These processes align directly with decomposition, abstraction, and algorithmic reasoning.

The effectiveness of PjBL in developing CT can be explained through its core instructional components. First, the use of real-world problem contexts requires students to formulate and decompose problems systematically. As noted by Fitrah et al. (2025) and Nabihah et al. (2025), authentic project tasks train students to identify essential elements of complex problems and generalize solutions across similar contexts. In the present study, project assignments required students to analyze real-life data and construct mathematical models, thereby strengthening abstraction and generalization skills. Such activities transform mathematical tasks from procedural exercises into structured inquiry processes.

Second, collaborative group work and project presentations play a critical role in reinforcing computational processes. According to Habibi et al. (2025) and Zhang et al. (2024), collaboration enhances debugging processes and reflective thinking, as students articulate reasoning and evaluate peer solutions. The findings of this study indicate that group discussions facilitated deeper engagement in identifying patterns and revising solution strategies. Through peer interaction, students refined their algorithmic reasoning and clarified abstract representations. This confirms that social interaction in PjBL environments contributes significantly to CT development.

Third, the integration of technology enhances the explicit representation of algorithms and patterns. Studies highlight that tools such as GeoGebra, Scratch, and mathematical solvers facilitate pattern visualization and algorithmic simulation (Hanafi et al., 2025; Sangpom & Sangpom, 2025; Saragih et al., 2025; Hadi et al., 2021). Although technology integration varied in this study, students used digital resources to represent geometric transformations and analyze statistical trends. These visual and computational tools allowed learners to test and refine algorithms iteratively, strengthening both abstraction and procedural fluency.

Fourth, the role of teacher scaffolding remains essential in optimizing PjBL outcomes. Research by Setyawan et al. (2024) and Saad and Zainudin (2022) emphasizes that structured worksheets and CT-based rubrics help students design systematic algorithmic solutions. In this study, scaffolding was embedded through guiding questions and structured reflection prompts, which supported students in articulating explicit solution steps. This instructional design element likely contributed to the significant gains observed in CT posttest scores.

Beyond cognitive outcomes, PjBL also positively influenced students' engagement and attitudes toward mathematics. Consistent with findings by Rehman et al. (2024) and Chhabra and Gawande (2025), project-based environments foster intrinsic motivation and positive mathematical identity. Students reported greater interest and ownership of learning, which may have amplified the effectiveness of CT development. Motivation and self-regulation are recognized as supporting factors in computational reasoning, as engaged learners are more likely to persist in complex problem-solving tasks (Rina et al., 2025).

From a practical perspective, the findings suggest that mathematics teachers should prioritize project topics rich in representation and pattern structures, such as geometry, statistics, and linear programming, to maximize CT development (Fitrah et al., 2025; Sangpom & Sangpom, 2025; Hadi et al., 2021). Projects should explicitly require students to decompose problems, identify recurring structures, construct abstract models, and formulate algorithmic steps. Embedding CT indicators within assessment rubrics and pre–post testing instruments ensures systematic measurement of learning progress (Setyawan et al., 2024; Saad & Zainudin, 2022).

Overall, the discussion confirms that the objective of this study has been achieved. The implementation of Project-Based Learning significantly develops students' computational thinking in mathematics, particularly in decomposition, pattern recognition, and abstraction. Algorithmic thinking also improves but benefits from structured scaffolding. The results are consistent with experimental studies, meta-analyses, and systematic reviews demonstrating PjBL's effectiveness across educational contexts. By integrating authentic problems, collaborative learning, technological tools, and guided reflection, PjBL provides a comprehensive framework for cultivating CT skills aligned with the demands of 21st-century mathematics education.

Conclusion

Based on the findings and discussion, this study concludes that the implementation of Project-Based Learning (PjBL) significantly enhances students' Computational Thinking (CT) skills in mathematics learning. The quasi-experimental results demonstrate that students exposed to PjBL show

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substantially higher improvements in decomposition, pattern recognition, abstraction, and algorithmic thinking compared to those taught through conventional instruction. The large effect size indicates that PjBL is not only statistically effective but also pedagogically meaningful in fostering deeper mathematical reasoning and structured problem-solving abilities. The integration of real-world projects, collaborative learning, technology-supported exploration, and structured teacher scaffolding creates a learning environment that actively cultivates computational processes embedded in mathematical thinking. Therefore, this study confirms that systematic implementation of PjBL provides an effective instructional framework for developing students' computational thinking while simultaneously strengthening conceptual understanding and engagement in mathematics education.

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