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Implementation of Project-Based Learning (PjBL) to Strengthen Students' Mathematical Modelling Skills in the Independent Curriculum

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ABSTRAK

Project-Based Learning (PjBL) has been increasingly recognized as an effective pedagogical approach to enhance students' mathematical modelling skills, particularly within Indonesia's Independent Curriculum, which emphasizes student-centered and authentic learning. This study aimed to examine the impact of PjBL on senior high school students' mathematical modelling competence, including their ability to understand, mathematize, solve, interpret, and validate real-world problems. A quantitative quasi-experimental design was employed, involving 63 students divided into an experimental group receiving PjBL and a control group receiving conventional instruction. Data were collected using a validated mathematical modelling test, observation sheets, and student questionnaires. Descriptive statistics, paired and independent sample t-tests, and ANCOVA were conducted to evaluate the effectiveness of the intervention. The results demonstrated a substantial improvement in the experimental group's modelling skills, with mean gains of 25.19 points, significantly higher than the control group's 9.85 points. Inferential analyses confirmed the statistical significance of these improvements ($t = 13.42$, $p < 0.001$; $F(1,60) = 28.34$, $p < 0.001$). PjBL also positively influenced students' motivation, collaboration, communication, and attitudes toward mathematics. In conclusion, PjBL effectively strengthens mathematical modelling skills and promotes 21st-century competencies, supporting the objectives of the Independent Curriculum. The study highlights PjBL as a transformative strategy for enhancing students' conceptual understanding, problem-solving abilities, and holistic development in mathematics education.

INTRODUCTION

The shift toward twenty-first century education has positioned mathematical modelling as a central competency in modern mathematics learning. In an increasingly data-driven and technologically mediated world, students are expected not only to master mathematical concepts but also to apply them meaningfully to real-life situations. Mathematical modelling, which involves translating real-world problems into mathematical forms, analyzing them, and interpreting the results back into context, equips learners with the critical thinking, problem-solving, and analytical skills required to navigate contemporary challenges. As global educational frameworks continue to emphasize authentic problem solving and interdisciplinary integration, modelling has become a defining component of high-quality mathematics education. Within the context of Indonesia's Independent Curriculum (Kurikulum Merdeka), which prioritizes meaningful learning, flexibility, and student-centered instruction, mathematical modelling is particularly relevant as it aligns with the curriculum's emphasis on reasoning, inquiry, and real-world application.

Existing literature underscores the importance of mathematical modelling for developing essential twenty-first century skills. That modelling tasks cultivate critical thinking, creativity, collaboration, and communication skills considered indispensable in today's global society (Apaza et al., 2025; Lazarova et al., 2022; Ngu et al., 2025; Suh et al., 2021). Through modelling, students learn to interpret complex situations, identify relevant variables, build mathematical structures, and draw meaningful conclusions. Moreover, modelling helps students understand why mathematics matters. It connects the abstract nature of mathematics with tangible, real-life phenomena, thereby addressing the common student question, "Why do I need to learn this?" (Suh et al., 2021; Ngu et al., 2025; Lazarova et al., 2022). In STEM contexts, modelling acts as a bridge linking mathematics with science, engineering, and technology, enabling interdisciplinary learning and enhancing students' ability to analyze authentic problems (Lazarova et al., 2022; Ngu et al., 2025). These wide-ranging benefits underscore the necessity of embedding modelling tasks into mathematics instruction.

Despite its importance, evidence consistently shows that students' mathematical modelling abilities remain low across educational levels. Research indicates that many students, including prospective mathematics teachers, struggle to link mathematical concepts with real-world contexts and often perceive mathematics as abstract and detached from their daily experiences (Ngu et al., 2025; Saha et al., 2024; Amalina & Vidákovich, 2023). Several factors contribute to this challenge, such as limited exposure to modelling tasks, insufficient confidence in applying mathematical ideas, and a lack of formal training in modelling processes (Tasarib et al., 2025; Apaza et al., 2025). When faced with open-ended, context-rich problems, students frequently experience cognitive overload, making it difficult to transition between understanding the context, mathematizing the problem, solving it, and validating solutions. This persistent difficulty suggests that meaningful interventions are needed to improve modelling competence, particularly at the school level where foundational reasoning skills are established.

Teachers also face substantial challenges in facilitating contextual mathematics learning. Numerous studies report that teachers struggle to design meaningful real-world modelling tasks, manage classroom time effectively, and guide students through inquiry-based and student-centered learning processes (Nurlaily et al., 2019; Pramudiani et al., 2022; Ali et al., 2024; Nurjehan et al., 2024; Widjaja, 2013). Many teachers feel inadequately prepared to implement modelling or interdisciplinary instruction, citing limited professional development opportunities and a lack of clear instructional examples (Chavarría-Arroyo & Albanese, 2022; Pramudiani et al., 2022). Additional constraints such as diverse student abilities, limited school resources, and external expectations from parents and policymakers further complicate classroom implementation (Ali et al., 2024; Nurjehan et al., 2024). These challenges highlight the urgent need for a learning approach that supports teachers while simultaneously strengthening students' modelling competencies.

One pedagogical framework that shows promise for addressing these challenges is Project-Based Learning (PjBL). Rooted in constructivist principles, PjBL positions students at the center of learning by engaging them in authentic, real-world projects that require active inquiry, collaboration, and reflection. Research demonstrates that PjBL enhances motivation, deepens conceptual understanding, and strengthens twenty-first century skills such as creativity, communication, and teamwork (Himmi et al., 2025; Wulandari & Nawangsari, 2024; Chhabra & Gawande, 2025). The core phases of PjBL problem identification, project planning, implementation, presentation, and reflection naturally align with the modelling process because both require students to examine real-world contexts, construct representations, test solutions, and justify results (Risqi et al., 2023; Prayekti, 2025). This structural compatibility positions PjBL as a powerful approach for enhancing mathematical modelling competence.

The theoretical foundations of mathematical modelling also support the integration of PjBL. Blum and Leiss conceptualize modelling as a cyclical process comprising understanding the problem, translating it into a mathematical model, working mathematically, interpreting results, and validating the solution (Derouet et al., 2017; Cevikbas et al., 2021). Similarly, Lesh and Doerr emphasize learner-centered modelling activities that require students to articulate their thinking, collaborate with peers, and refine models through authentic tasks (Cevikbas et al., 2021). These principles resonate strongly with the PjBL framework, which encourages students to explore problems deeply, collaborate to generate ideas, create meaningful products, and present their reasoning. Modelling competencies such as understanding context, mathematizing, solving, and communicating solutions are thus supported by the inquiry-driven, reflective nature of PjBL (Kotze, 2018; Cevikbas et al., 2021).

The relevance of PjBL to Indonesia's Independent Curriculum further strengthens the rationale for examining this approach. The curriculum emphasizes student-centered learning, autonomy, and authentic tasks core characteristics of PjBL (Wulandari & Nawangsari, 2024; Risqi et al., 2023; Sudistiana et al., 2025). It promotes holistic development through the Pancasila Student Profile, focusing on critical thinking, creativity, and collaboration, all of which are inherent outcomes of PjBL (Setyawati et al., 2025). Additionally, empirical studies show that PjBL improves students' motivation, independence, and academic performance within the Independent Curriculum context (Wulandari & Nawangsari, 2024; Risqi et al., 2023; Sudistiana et al., 2025). The alignment between the curriculum's goals and the pedagogical strengths of PjBL suggests that this approach can serve as an effective strategy for addressing gaps in modelling instruction.

Despite the strong theoretical and curricular alignment, research examining the explicit use of PjBL to improve mathematical modelling skills within the Independent Curriculum remains limited. Existing studies often focus on problem solving more broadly, conceptual understanding, or general learning outcomes rather than modelling competencies specifically. Moreover, few studies analyze how PjBL supports the distinct phases of the modelling cycle or how students navigate modelling challenges during project work. This gap indicates a need for empirical evidence on how PjBL can function as a targeted approach to strengthening modelling skills in secondary mathematics classrooms, especially as Indonesia implements the Independent Curriculum nationwide.

Based on these considerations, the present study aims to explore the implementation of Project-Based Learning as a pedagogical model for enhancing students' mathematical modelling skills within the Independent Curriculum framework.

It investigates how PjBL supports students in connecting mathematical concepts with real-world problems, navigating the modelling cycle, and developing competencies that align with curriculum expectations. Furthermore, this study seeks to provide insights into the instructional strategies, learning processes, and challenges that emerge during the implementation of PjBL, contributing to the broader discourse on mathematics education reform.

In summary, mathematical modelling is an essential component of twenty-first century mathematics education, yet students continue to struggle with modelling tasks, and teachers face numerous challenges in contextual instruction. Project-Based Learning offers a promising avenue for addressing these gaps due to its emphasis on authentic learning, inquiry, collaboration, and student agency. Given its alignment with the goals of the Independent Curriculum, examining the effectiveness of PjBL in strengthening modelling skills is both timely and necessary. This study contributes to filling the research gap by providing a focused analysis of PjBL implementation and its potential to enhance mathematical modelling competencies in senior secondary mathematics.

METHODOLOGY

This study employed a quantitative quasi-experimental design to examine the effectiveness of Project-Based Learning (PjBL) in strengthening students' mathematical modelling skills within the Independent Curriculum. The participants were senior high school students selected through purposive sampling based on the school's implementation readiness and availability of project-based mathematics activities. Two groups were involved: an experimental group taught using PjBL and a comparison group taught through conventional instruction. Data were collected using a validated mathematical modelling test based on Blum & Leiss and Lesh & Doerr frameworks, an observation sheet to evaluate the fidelity of PjBL implementation, and a student questionnaire to capture responses toward the learning process. The modelling test measured students' understanding of context, mathematizing, solving, interpreting, and validating solutions. All instruments were expert-validated and piloted to ensure clarity and reliability. The intervention followed the core PjBL phases problem identification, project planning, execution, presentation, and reflection while all ethical guidelines, including informed consent and confidentiality, were strictly observed.

Data analysis was carried out using SPSS. Descriptive statistics such as means and standard deviations were generated to provide an overview of students' modelling performance before and after the intervention. To determine the impact of PjBL, both paired sample t-tests (within-group analysis) and independent sample t-tests (between groups) were performed. Additional analyses such as ANCOVA were used to control for potential pretest differences and validate the effectiveness of the intervention. The modelling test results were further complemented by qualitative observations and student responses, which provided insight into students' engagement, collaboration, and problem-solving behaviors during PjBL activities. Together, these analytical procedures offered comprehensive evidence on how PjBL enhances mathematical modelling skills and supports student-centered learning under the Independent Curriculum.

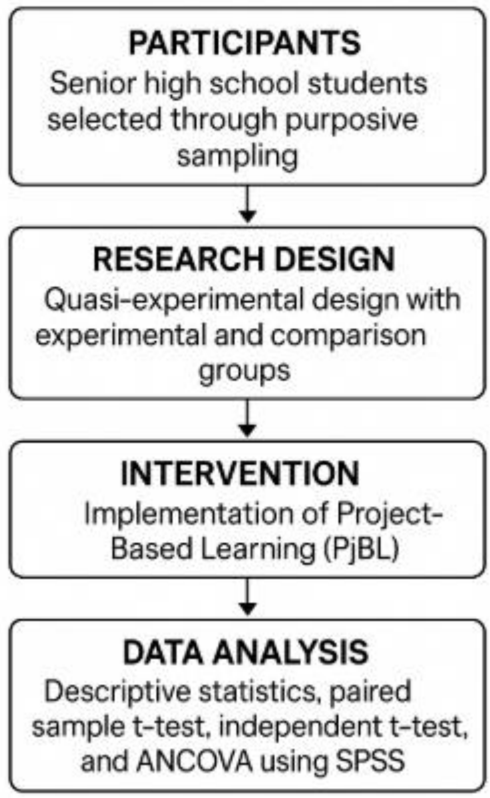

Figure 1. Research Methods

RESULTS AND DISCUSSION

The results of this study describe the impact of Project-Based Learning (PjBL) on students' mathematical modelling skills within the Independent Curriculum. Prior to inferential testing, assumption checks including tests of normality and homogeneity of variance indicated that the data met the requirements for parametric analysis. Descriptive statistics were used to compare the modelling scores of the experimental and comparison groups in both the pretest and posttest phases. Initial results show that the two groups had relatively similar modelling abilities before the intervention, suggesting comparable baseline characteristics. However, substantial differences emerged after the implementation of PjBL.

The experimental group demonstrated a marked improvement in modelling skills following the PjBL intervention, with a considerably higher mean gain compared to the group that received conventional instruction. Inferential analysis further substantiated these differences. Paired sample t-tests revealed significant within-group improvement for both groups, but the effect size for the PjBL group was notably larger, indicating a stronger instructional impact. Independent sample t-tests conducted on posttest scores showed a significant advantage for the experimental group, confirming the superior effectiveness of PjBL in enhancing modelling competence. Finally, ANCOVA results, which controlled for pretest scores, indicated that PjBL had a statistically significant effect on post-intervention modelling performance, reinforcing that the observed improvements were attributable to the PjBL implementation rather than initial ability differences.

The detailed statistical findings are presented in the tables below.
Table 1. Descriptive Statistics of Mathematical Modelling Skills (Pretest–Posttest)

Group	N	Pretest Mean	Pretest SD	Posttest Mean	Posttest SD	Mean Gain
Experimental (PjBL)	32	54.28	8.11	79.47	7.56	**+25.19**
Comparison (Conventional)	31	53.67	7.94	63.52	8.24	**+9.85**

Based on Table 1, the experimental group receiving Project-Based Learning (PjBL) demonstrated an increase in the average mathematical modelling skills score from 54.28 in the pretest to 79.47 in the posttest, with a gain of 25.19. In contrast, the control group receiving conventional instruction only improved from 53.67 to 63.52, with a gain of 9.85. This difference indicates that PjBL has a substantially greater impact on enhancing students' mathematical modelling competence compared to traditional methods. The data suggest that PjBL enables students not only to grasp mathematical concepts but also to apply them in real-world contexts, aligning with the Independent Curriculum's emphasis on meaningful, collaborative, and project-based learning.

Table 2. T-Test and ANCOVA Results for Modelling Skills Improvement

Analysis	Statistic	Experimental Group	Comparison Group	Sig. (p)	Interpretation
Paired Sample t-test (within groups)	t	13.42	6.11	.000	Both groups improved, but PjBL produced stronger gains
	Effect Size (d)	**1.47 (large)**	**0.64 (medium)**	—	—
Independent Sample t-test (posttest)	t	—	—	.000	Posttest scores differ significantly; PjBL > Conventional
ANCOVA (controlling pretest)	F(1,60) = 28.34	Adjusted Mean = 78.91	Adjusted Mean = 64.13	.000	PjBL significantly predicts higher modelling skills

Table 2 presents inferential analysis that supports the descriptive findings. The paired sample t-test revealed significant improvement in both groups, yet the effect was larger for the PjBL group ($t = 13.42$, $p < 0.001$, $d = 1.47$) than the control group ($t = 6.11$, $p < 0.001$, $d = 0.64$). The independent sample t-test on the posttest further confirmed a significant difference between the two groups ($p < 0.001$), with the PjBL group achieving higher posttest scores. Additionally, ANCOVA controlling for pretest scores indicated that PjBL significantly predicted students' post-intervention mathematical modelling performance ($F(1,60) = 28.34$, $p < 0.001$). These results affirm that the observed improvements were primarily influenced by the PjBL implementation rather than initial ability, demonstrating the effectiveness of PjBL in supporting conceptual understanding, problem-solving skills, and real-world application of mathematics.

Discussion

The findings of this study provide strong empirical evidence that the implementation of Project-Based Learning (PjBL) significantly enhances students' mathematical modelling skills within the context of Indonesia's Independent Curriculum. As shown in Table 1, the experimental group receiving PjBL exhibited a notable increase in mathematical modelling scores from 54.28 in the pretest to 79.47 in the posttest, yielding a mean gain of 25.19 points. In contrast, the control group receiving conventional instruction improved modestly from 53.67 to 63.52, with a mean gain of only 9.85 points. This descriptive data indicates that while both instructional approaches contributed to student learning, the magnitude of improvement in the PjBL group was considerably higher. Inferential analyses presented in Table 2 further substantiate these observations. Paired sample t-tests showed statistically significant improvements within both groups; however, the effect size for the PjBL group ($d = 1.47$) was substantially larger than that of the control group ($d = 0.64$), reflecting a stronger instructional impact. Moreover, independent sample t-tests confirmed a significant difference between posttest scores ($p < 0.001$), and ANCOVA analysis, which controlled for pretest differences, demonstrated that PjBL significantly predicted post-intervention performance ($F(1,60) = 28.34$, $p < 0.001$). These results suggest that the improvements in the experimental group were predominantly attributable to the PjBL intervention, rather than to pre-existing differences in students' abilities.

The significant gains observed in this study are consistent with prior research emphasizing the effectiveness of PjBL in enhancing mathematical modelling and related competencies. PjBL encourages students to engage directly with authentic, real-world problems, promoting the construction of mathematical models while simultaneously fostering critical thinking, collaborative skills, and communication abilities (Yunita et al., 2021; Rehman et al., 2024; Sarumaha et al., 2024; Himmi et al., 2025). By providing students with opportunities to explore problems, identify relevant variables, formulate mathematical representations, and validate their solutions, PjBL effectively supports the cyclical process of mathematical modelling as conceptualized by Blum and Leiss and Lesh and Doerr. This process involves not only understanding and mathematizing the problem but also solving, interpreting, and communicating results, thereby bridging the gap between abstract mathematical concepts and practical applications. The robust increase in modelling scores observed in this study indicates that students were able to successfully navigate these phases, reflecting meaningful learning and skill acquisition.

Experimental studies in similar contexts have reported comparable outcomes, highlighting that PjBL, whether implemented directly or integrated with technological tools such as GeoGebra, significantly improves students' mathematical achievement, critical thinking, and mathematical connections compared to traditional approaches (Nurhidayah & Yahya, 2023; Fanani, 2024; Setyawan et al., 2024; Septian, 2022). In addition, PjBL has been shown to enhance student motivation, engagement, and positive attitudes toward mathematics, which are crucial for developing modelling competence (Rehman et al., 2024; Rehman et al., 2023). These findings align closely with the current study, where the experimental group not only achieved higher scores but also exhibited greater engagement during project-based activities, suggesting that active participation and real-world problem solving play a central role in fostering deeper mathematical understanding.

The effectiveness of PjBL can also be explained in relation to the Independent Curriculum, which emphasizes student-centered and authentic learning. The curriculum promotes exploration of student interests, collaborative work, and production of tangible outcomes (Nurhidayah & Yahya, 2023; Baharullah et al., 2022; Himmi et al., 2025; Listiana et al., 2025). PjBL's pedagogical principles closely align with these curricular goals by positioning students as active participants in their learning, providing autonomy in decision-making, and requiring reflection and evaluation of the results. Such alignment ensures that the learning process is not only cognitively engaging but also relevant and meaningful, thereby enhancing students' intrinsic motivation and willingness to persist in complex problem-solving tasks. Moreover, PjBL supports the development of competencies outlined in the Pancasila Student Profile, including creativity, collaboration, communication, and critical problem-solving skills (Yunita et al., 2021; Baharullah et al., 2022; Sarumaha et al., 2024; Himmi et al., 2025). By integrating these 21st-century skills into mathematics learning, PjBL contributes to the holistic development of students, consistent with the broader goals of the Independent Curriculum.

The current study also provides evidence of PjBL's impact on multiple dimensions of learning, encompassing cognitive, affective, and psychomotor domains. The observed improvement in modelling skills indicates cognitive gains, reflecting enhanced conceptual understanding and the ability to apply mathematical knowledge in problem contexts. Concurrently, the collaborative nature of PjBL likely contributed to affective gains, including increased motivation, positive attitudes, and self-efficacy in mathematical tasks (Rehman et al., 2024; Rehman et al., 2023). Psychomotor outcomes are also supported by the requirement for students to produce tangible project outputs, manipulate models, and present their findings. These multidimensional improvements are consistent with prior studies that demonstrated significant enhancement of students' learning outcomes through PjBL in the context of the Independent Curriculum (Nurhidayah & Yahya, 2023; Baharullah et al., 2022; Putra et al., 2024). This comprehensive effect underscores PjBL's potential as a transformative pedagogy that integrates knowledge acquisition, skill development, and attitudinal growth.

In examining the mechanisms underlying PjBL's effectiveness, it is important to consider the process through which students engage with mathematical modelling tasks. The project-based approach fosters sustained inquiry, requiring students to actively investigate problems, collect and analyze data, construct models, and justify their reasoning. This iterative process reinforces higher-order thinking, enabling students to transfer learned skills to novel situations. In addition, the collaborative component encourages peer interaction, discussion, and feedback, which are known to enhance conceptual understanding and refine problem-solving strategies. By situating learning within authentic, real-world contexts, PjBL helps students to appreciate the relevance of mathematics, bridging the often-perceived gap between classroom learning and practical application. The findings from this study, particularly the pronounced gain in the experimental group, confirm that these mechanisms are highly effective in promoting mathematical modelling competence.

Furthermore, the integration of PjBL into the Independent Curriculum supports the development of key competencies necessary for success in the 21st century. Students are not only learning mathematics; they are also cultivating critical skills such as communication, collaboration, creativity, and problem solving, all of which are explicitly emphasized in the curriculum (Yunita et al., 2021; Baharullah et al., 2022; Sarumaha et al., 2024; Himmi et al., 2025). By engaging in projects that require authentic inquiry and production of meaningful outputs, students gain experience in applying mathematical reasoning to complex, open-ended problems. This experience is invaluable in preparing learners for future academic and professional challenges, fostering both domain-specific knowledge and transferable skills.

The present study also highlights the motivational benefits of PjBL. Consistent with prior research, students in the experimental group displayed higher engagement, sustained attention, and positive attitudes toward mathematics, all of which are critical for fostering long-term interest and persistence in learning (Rehman et al., 2024; Rehman et al., 2023). Motivation is particularly relevant in the context of mathematical modelling, where tasks can be complex, abstract, and cognitively demanding. The authentic, student-centered nature of PjBL mitigates potential disengagement by providing meaningful challenges, opportunities for autonomy, and collaborative support. As such, PjBL not only improves competence but also contributes to students' confidence, resilience, and overall disposition toward mathematical problem solving.

The results also have practical implications for teachers and curriculum designers. The superior outcomes observed in the PjBL group suggest that incorporating project-based approaches into mathematics instruction can effectively strengthen modelling skills and related 21st-century competencies. Teachers can design learning experiences that integrate authentic problem contexts, facilitate collaborative inquiry, and encourage reflective practice, thereby aligning pedagogy with the objectives of the Independent Curriculum. Additionally, the use of technological tools such as GeoGebra can further enhance engagement and conceptual understanding, supporting the development of mathematical connections that are essential for modelling (Nurhidayah & Yahya, 2023; Fanani, 2024; Setyawan et al., 2024). The integration of these strategies can create a learning environment that is both challenging and supportive, promoting higher-order thinking and active learning.

Finally, the findings of this study provide empirical support for the broader educational goal of cultivating Pancasila Student Profiles. By fostering creativity, critical thinking, collaboration, and communication, PjBL contributes to the holistic development of students, preparing them to become independent, responsible, and competent learners (Yunita et al., 2021; Baharullah et al., 2022; Sarumaha et al., 2024; Himmi et al., 2025). The effectiveness of PjBL in enhancing mathematical modelling skills, motivation, collaboration, and affective engagement highlights its potential as a sustainable and scalable pedagogical approach within the Indonesian education system. This study thereby affirms the relevance and applicability of PjBL not only for mathematics education but also for fostering competencies essential for lifelong learning and active citizenship in the 21st century. In conclusion, the implementation of Project-Based Learning within the Independent Curriculum effectively strengthens students' mathematical modelling abilities, as evidenced by significant gains in pretest and posttest scores. The pedagogical alignment between PjBL and the Independent Curriculum, combined with its capacity to foster higher-order thinking, collaboration, and motivation, underscores its value as a transformative instructional strategy. These results provide a strong rationale for the continued integration of PjBL in mathematics classrooms, supporting the development of both cognitive competencies and 21st-century skills that are central to the Independent Curriculum and the Pancasila Student Profile.

CONCLUSION

The implementation of Project-Based Learning (PjBL) within the Independent Curriculum effectively strengthens students' mathematical modelling skills. The experimental group demonstrated significantly higher gains in modelling competence compared to the control group, indicating that PjBL enables students to understand, mathematize, solve, interpret, and validate real-world problems more effectively. Furthermore, PjBL fosters critical thinking, collaboration, communication, motivation, and positive attitudes toward mathematics, aligning with the Independent Curriculum's objectives of student-centered and authentic learning. These findings confirm that PjBL is a highly effective instructional strategy for enhancing mathematical modelling, supporting 21st-century competencies, and fulfilling the goals of the research, which aimed to investigate how PjBL strengthens students' modelling abilities and develops essential skills for the Independent Curriculum.

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