The effectiveness of the project-based learning model with the STEAM approach in the woodworking practice course

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Abstract: The transformation of vocational education requires learning models that not only emphasize project completion but also ensure product quality aligned with industry standards. This study investigates the effectiveness of integrating Project-Based Learning (PjBL) with a STEAM approach and inspection-based Quality Control (QC) in enhancing student competencies in a Woodworking Practice course. A quasi-experimental design with a non-equivalent control group was employed. The experimental group experienced PjBL–STEAM integrated with three stages of inspection-based QC (incoming, in-process, and final inspection), while the control group received conventional instruction without systematic QC integration. Data were collected through cognitive tests and product quality assessments using structured rubrics. The findings indicate that students exposed to the integrated model demonstrated significantly higher cognitive achievement and produced furniture products of superior quality compared to those in the control group. Improvements were observed across key indicators, including finishing quality, structural strength, aesthetics, and functionality. The results suggest that embedding systematic inspection-based QC within PjBL–STEAM not only strengthens conceptual understanding but also fosters precision, quality awareness, and industry-relevant vocational skills. This study contributes to vocational education by proposing a structured integration of industrial quality inspection practices into project-based STEAM learning. The model supports the development of work-ready graduates and aligns with contemporary vocational education reforms that emphasize contextual learning, industry relevance, and 21st-century competencies.

Keywords: Project-Based Learning, STEAM, Quality Control, Vocational Education, Wooden Furniture

1. Introduction

Global changes marked by the 4.0 industrial revolution and the emergence of the Society 5.0 paradigm demand transformation in the education system, especially in the vocational field, in order to produce adaptive and work-ready human resources. Technical and Vocational Education and Training (TVET) plays a strategic role in preparing the workforce with technical skills (hard skills) and 21st-century skills such as creativity, collaboration, and problem-solving that are in line with the needs of modern industry (Kurup et al., 2019; Li et al., 2020). TVET also plays an important role in bridging the gap between theoretical knowledge and practical application in the world of work, as well as supporting sustainable economic development by empowering a competent workforce (Chistyakov et al., 2023; Najeeb & Memon, 2022).

In Indonesia, vocational education plays an important role as the spearhead in providing skilled workers who meet the needs of industry. The government, through the Ministry of Education, Culture, Research, and Technology, has encouraged the strengthening of vocational education through programs to revitalize vocational schools, vocational campuses, and the Merdeka Belajar–Kampus Merdeka (MBKM) policy. These efforts are in line with national challenges related to the high skills mismatch between vocational graduates and labor market needs. This condition shows that vocational education graduates often do not fully master the technical and non-technical skills required by the industrial world, especially in terms of technology application, design creativity, and product quality standards (Ahmad et al., 2023). Therefore, higher education institutions that provide vocational education, including engineering-based universities, have a major responsibility to ensure that the learning process truly brings students closer to the realities of the world of work.

Universitas Negeri Padang (UNP) as one of the universities that develops vocational education in the field of engineering has workshop facilities that function as practical laboratories to bring students closer to the real world of work. The Civil Engineering Department has several workshops, including a concrete workshop, a plumbing and sanitation workshop, and a woodworking workshop, which is used as the main facility for the Woodworking Practice course. This course is oriented towards vocational learning, which requires students to not only understand theoretical concepts, but also master psychomotor skills in the use of tools, machines, and wood construction techniques. Previous research confirms that workshops in engineering education play an important role in improving students' practical skills because they provide contextual learning experiences that closely resemble industry demands (Ruslan et al., 2021). In addition, through workshop activities, students are also trained to produce real products, such as wooden furniture, which can be used as a benchmark for vocational skills and work readiness (Marta et al., 2024; Rahim et al., 2024).

Although the existence of the woodworking workshop has provided students with practical experience, the quality of the furniture products they produce remains far below market standards and industrial requirements. Student products generally face issues related to dimensional accuracy, joint strength, finishing neatness, and low aesthetic value, making them fall short of the quality criteria for commercial furniture. This problem primarily arises because the learning process has not yet implemented a continuous quality control (QC) system, starting from material selection to final product evaluation. In fact, QC is an essential aspect of vocational education to ensure that students' skills meet industry standards and remain relevant to workplace demands (Chistyakov et al., 2023; Jalinus et al., 2017). Preliminary studies also indicate a significant gap between student furniture quality and industry standards. On average, the quality of student products only reached a score of 68.8 (fair category), far below the minimum industry benchmark of "good" (≥83). This gap was evident in nearly all aspects, especially dimensional accuracy, joint strength, and finishing quality, which are critical indicators in wood product assessment. This phenomenon reinforces that the absence of QC implementation in woodworking practice courses directly impacts the low quality of the products produced. Consequently, vocational graduates risk facing a skills mismatch, as they are not accustomed to modern furniture industry standards that emphasize precision, efficiency, and sustainable quality (Ahmad et al., 2023; Rahim et al., 2024).

To address this issue, vocational learning innovation is required, one that not only focuses on project completion but also ensures product quality through systematic QC implementation. An inspection-based QC method, covering incoming inspection during material selection, in-process inspection during production, and final inspection at the end product stage is considered an ideal approach for woodworking practice. A study demonstrated that applying QC, which includes product planning, raw material control (incoming quality control), and production process supervision (in-process quality control), significantly improves furniture productivity and quality through visual evaluation, durability, and compliance with ISO-based standards (Prima et al., 2024). Inspection-based QC can be integrated into the Project-Based Learning (PjBL) model with a STEAM approach, as this model emphasizes student engagement in real projects, collaborative learning, and problem-solving that requires the integration of science, technology, engineering, arts, and mathematics (Li et al., 2020; Najeeb & Memon, 2022). Integrating QC into PjBL and STEAM ensures that learning not only produces furniture products but also develops more comprehensive vocational competencies, including technical skills, design creativity, problem-solving abilities, and a work ethic grounded in industry quality standards (Ahmad et al., 2023; Rahim et al., 2024).

This study is important because it makes a tangible contribution to developing vocational learning models that are more relevant to industrial demands. The integration of inspection-based QC into the PjBL–STEAM model is expected not only to improve the quality of student furniture products but also to foster comprehensive vocational competencies encompassing cognitive, psychomotor, and affective domains. QC, applied systematically from the initial stages through to the final product, familiarizes students with industry quality standards, thereby enhancing their work readiness. The urgency of this study also aligns with the Merdeka Belajar–Kampus Merdeka (MBKM) policy, which emphasizes contextual learning experiences, collaboration, and 21st-century skills to strengthen the global competitiveness of vocational graduates (Marta et al., 2024; Rahim et al., 2024). Thus, this research not only contributes to improving the quality of learning in woodworking practice classes but also has the potential to serve as a reference in policy formulation and curriculum development for technical vocational education in Indonesia.

2. Methods

This study employed a quasi-experimental method using a Non-Equivalent Control Group Design to examine the effectiveness of integrating Project-Based Learning (PjBL) with a STEAM approach and inspection-based Quality Control (QC) in the Woodworking Practice course. The research was conducted during one semester (16 meetings) at the Civil Engineering Department, Faculty of Engineering, Universitas Negeri Padang. Two intact classes were selected through purposive sampling, consisting of an experimental group ($n = 16$) and a control group ($n = 16$).

The experimental group received PjBL–STEAM integrated with three-stage inspection-based QC (incoming, in-process, and final inspection), while the control group received conventional practice-based instruction without systematic QC. The research procedure began with a pre-test to measure students' initial cognitive competence, followed by the implementation of the treatment over 12 instructional meetings, and concluded with a post-test and product quality assessment.

Data were collected using validated cognitive achievement tests and furniture product assessment rubrics covering finishing quality, design aesthetics, structural strength, and functionality. Instrument validity was established through expert judgment and content validity indexing, while reliability was tested using Cronbach's alpha ($\alpha > 0.70$), indicating acceptable internal consistency.

Data were analyzed using descriptive statistics, N-gain analysis to determine learning improvement, and an independent sample t-test to examine differences between groups at a 0.05 significance level. The research procedure was structured in a sequential flowchart comprising preparation, treatment implementation, evaluation, and statistical analysis stages. Ethical clearance was obtained from the Faculty Research Ethics Committee, and informed consent was secured from all participating students prior to data collection.

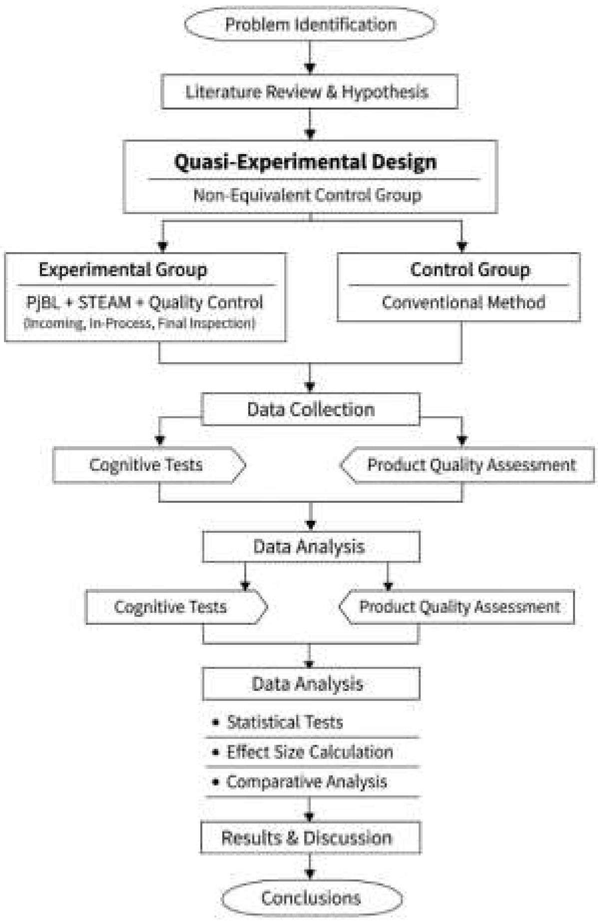

Figure 1. Research procedure flowchart of the quasi-experimental design

3. Results

The findings of this study demonstrate a highly significant effect of integrating Project-Based Learning (PjBL)–STEAM with inspection-based Quality Control (QC) on improving students' cognitive abilities and product quality in the Woodworking Practice course. Table 1 presents the average pre-test and post-test scores of students in both the experimental and control groups. The post-test mean score in the experimental group reached 85.11, far exceeding the control group's score of 70.33.

Table 1. Average student knowledge scores

Class	Pre-test	Post-test
Experimental	11.39	85.11
Control	11.11	70.33

Figure 2 illustrates the comparison of average pre-test and post-test scores between the experimental and control groups. The graph shows that the experimental group experienced a much greater improvement compared to the control group. These findings align with the view that PjBL in vocational contexts enhances student motivation as well as productive skills (Ahmad et al., 2023). This study strengthens the evidence that PjBL is effective in vocational education, and the addition of inspection-based QC makes it more closely aligned with quality practices in the furniture industry.

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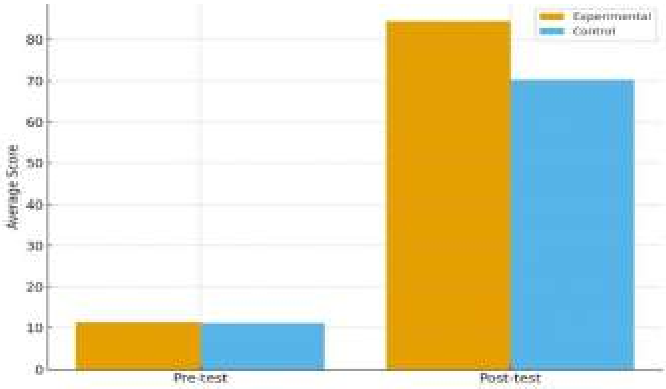

Figure 2. Comparison of average pre-test and post-test scores

Figure 3 shows the distribution of students' post-test scores. Both figures confirm that the experimental class consistently outperformed the control class.

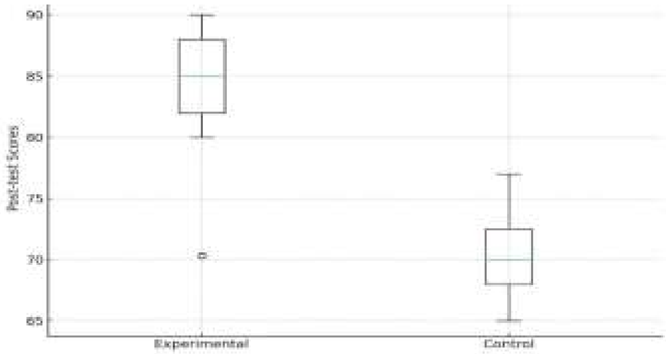

Figure 3. Distribution of post-test scores

This improvement is also reflected in the N-gain scores (Figure 4), with the experimental group achieving 0.83 (high category), higher than the control group's 0.66 (moderate category). This indicates the effectiveness of PjBL–STEAM combined with inspection-based QC.

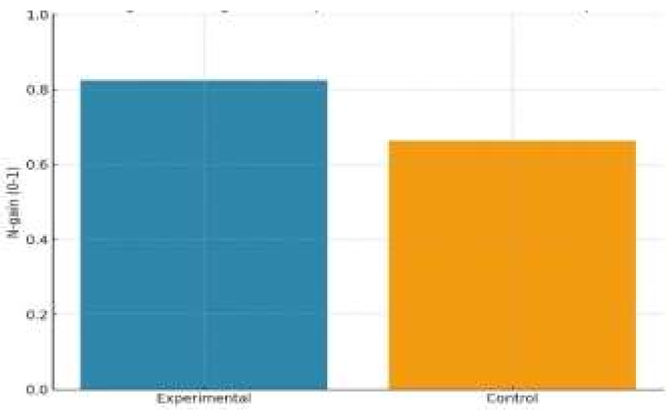

Figure 4. Comparison of N-gain between groups

These results are consistent with findings that implementing PjBL–STEAM significantly enhances creativity and cognitive outcomes in vocational students (Ekayana et al., 2025). Similarly, PjBL–STEAM in welding technology courses has been shown to significantly improve students' cognitive, affective, and psychomotor domains (Rahim et al., 2024). The significant improvement observed in the experimental group also supports evidence that PjBL–STEAM effectively develops engineering students' 21st-century skills (Oanh & Dang, 2025). Likewise, PjBL–STEAM has been found to increase active student engagement and enhance learning effectiveness in science and technology education (Chistyakov et al., 2023). Thus, this study not only confirms the effectiveness of PjBL–STEAM in international contexts but also extends its scope by demonstrating the added value of integrating inspection-based QC to strengthen vocational learning outcomes.

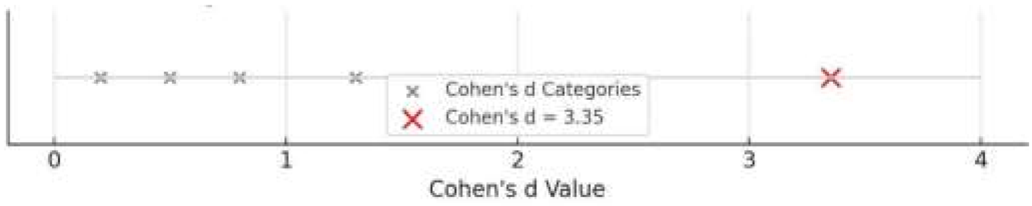

Figure 5. Effect Size Visualization (Cohen's d)

Inferential analysis using the independent t-test yielded t = 12.03 with p-value = 8.52×10^{-14}, indicating a highly significant difference between groups. The Cohen's d effect size of 3.35 (Figure 5) reflects a very large effect category. This value even surpasses the average effect size reported in international PjBL–STEAM meta-analyses. Previous meta-analytical evidence on STEM–PBL effectiveness reports consistently large effect sizes in enhancing student creativity and achievement (Cheng & Kinoshita, 2024). Therefore, the present study's results not only demonstrate a consistent positive influence but also highlight the amplifying role of inspection-based QC in enhancing the impact of PjBL–STEAM. These findings support the conclusion that technology-based STEM/STEAM learning strategies have a significant effect on student achievement (Hiğde & Aktamış, 2022; Suherman et al., 2025). The very large effect size observed in this study is rarely reported in previous research, indicating that QC integration substantially strengthens the impact of PjBL–STEAM beyond earlier findings.

From the perspective of furniture product quality, the experimental class scored higher across all indicators compared to the control class. Table 2 presents the comparison of average product quality scores in four main indicators: finishing quality, design aesthetics, structural strength, and product functionality.

Table 2. Average furniture product quality scores

Indicator	Experimental	Control
Finishing quality	88.25	74.75
Design aesthetics	87.00	70.75
Structural strength	84.25	70.50
Product functionality	90.00	70.25

Figure 6 presents a radar chart comparing the performance of the experimental and control groups across four product quality indicators: finishing quality, design aesthetics, structural strength, and product functionality. The visualization clearly shows that the experimental group consistently achieved higher scores in all dimensions. This pattern indicates that integrating inspection-based Quality Control (QC) within the PjBL–STEAM framework systematically enhances multidimensional product quality in vocational woodworking practice.

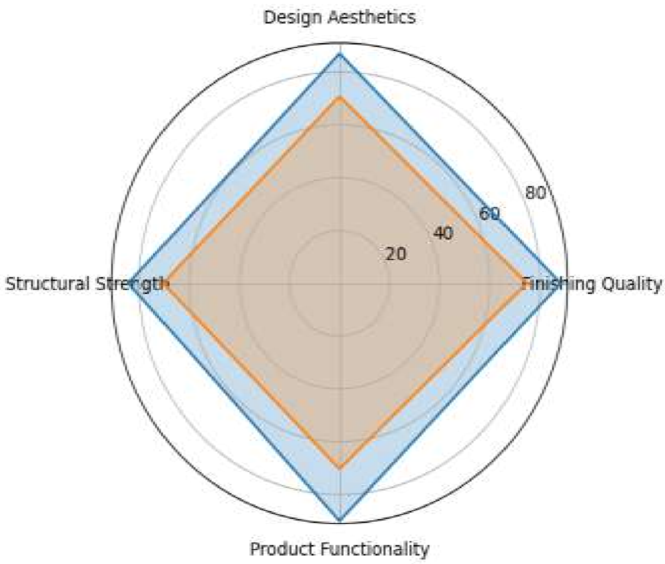

Figure 6. Radar chart of furniture product quality

Figure 7 illustrates the magnitude of score differences between the experimental and control groups for each quality indicator. The largest gap was observed in product functionality (+19.75 points), followed by finishing quality (+13.50), design aesthetics (+16.25), and structural strength (+13.75). These findings demonstrate that the integration of inspection-based QC not only improves technical precision but also significantly strengthens product usability and market-oriented performance.

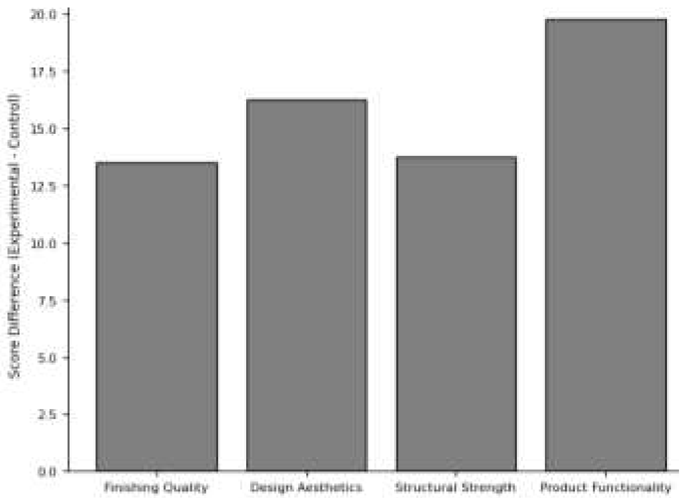

Figure 7. Gap analysis of furniture product quality

These findings are consistent with evidence that inspection-based QC in vocational furniture education enhances productivity and quality in line with ISO standards (Prima et al., 2024). They also align with research highlighting the importance of integrating design creativity within STEAM to produce consumer-oriented innovative products (Marta et al., 2024). Furthermore, the application of quality management methodologies in wooden furniture production has been shown to improve both efficiency and industry compliance (Skorupińska et al., 2024). Consequently, the student products in this study were more relevant to modern furniture industry standards.

Moreover, the successful implementation of three-stage inspection-based QC demonstrates a substantial contribution to ensuring product quality consistency. This is consistent with findings that zero-defect inspection strategies are effective in preventing defects at the earliest stage (Zhou & Chen, 2025), while in-process QC plays a crucial role in maintaining sustainable manufacturing quality (Karim et al., 2025). Therefore, integrating inspection-based QC into PjBL–STEAM not only strengthens cognitive and psychomotor learning outcomes but also introduces an innovative transfer of industry-level quality practices into academic settings.

Overall, this study confirms that integrating PjBL–STEAM with inspection-based QC significantly improves both cognitive achievement and product quality. These findings expand upon previous studies that primarily focused on multidomain skills and learning motivation (Ahmad et al., 2023; Rahim et al., 2024) by introducing a new dimension of QC-based product quality aligned with industry standards. The novelty of this study lies in embedding three-stage inspection-based QC into PjBL–STEAM. While most previous research emphasized cognitive and multidomain skills improvement, this study adds the critical element of QC-driven product quality. Hence, its contribution is not only pedagogical but also practical in enhancing vocational graduates' readiness for the workforce.

4. Discussion

This study was initiated to address a clearly identified gap in vocational woodworking education at Universitas Negeri Padang, namely the discrepancy between student-produced furniture quality (mean score 68.8) and industry benchmarks (≥83), which was attributed to the absence of systematic Quality Control (QC) integration. The findings demonstrate that embedding inspection-based QC within the PjBL–STEAM framework significantly reduces this gap, both cognitively and productively. From a theoretical standpoint, this result aligns with recent TVET transformation frameworks emphasizing industry alignment as a determinant of vocational relevance (Kebede, 2024). These frameworks argue that vocational effectiveness is achieved not solely through active learning models but through structural synchronization with industrial production logic. The present study empirically substantiates this argument by demonstrating that QC integration functions as a pedagogical bridge between workshop learning and industrial standards.

The substantial cognitive improvement (N-gain = 0.83; very large effect size) indicates that the integration of QC strengthens the epistemic rigor of PjBL–STEAM. Previous research has consistently shown that PjBL–STEAM enhances creativity and multidomain competencies (Cheng & Kinoshita, 2024; Ekayana et al., 2025; Oanh & Dang, 2025). However, these studies primarily examined higher-order thinking and engagement outcomes without embedding formal quality assurance mechanisms. The significantly larger effect size in this study suggests that structured inspection stages create iterative feedback loops that intensify reflective learning, consistent with experiential learning and constructive alignment principles in vocational pedagogy (Chistyakov et al., 2023). Unlike prior implementations where projects emphasized completion and creativity, the present intervention embedded measurable quality checkpoints, thereby increasing cognitive accountability and procedural discipline.

In terms of product quality outcomes, the findings demonstrate marked superiority in finishing, structural strength, aesthetics, and functionality. These results extend beyond earlier PjBL–STEAM studies, which reported improved student engagement but did not systematically measure industrial-grade product indicators (Ahmad et al., 2023; Rahim et al., 2024). The present findings resonate strongly with quality management literature in manufacturing contexts. Structured quality methodologies in wooden furniture production have been confirmed to significantly enhance dimensional precision and finishing consistency (Skorupińska et al., 2024). Similarly, in-process quality control has been shown to ensure production stability and reduce defects in sustainable manufacturing systems (Goyal et al., 2019; Yadav et al., 2025). By operationalizing incoming, in-process, and final inspections within a pedagogical model, this study demonstrates that industrial quality logic can be effectively transferred into educational settings.

A critical distinction between the present findings and previous STEAM-based vocational studies lies in the operationalization of inspection as a formative pedagogical intervention. Zero-defect incoming inspection strategies have been shown to substantially reduce downstream manufacturing errors (Zhou & Chen, 2025). Preventive quality verification at the material selection stage plays a critical role in minimizing cumulative defects and ensuring product reliability throughout the production cycle. In contrast, most educational PjBL–STEAM implementations have not incorporated preventive inspection as part of learning design. The higher functionality score (+19.75 gap) observed in this study suggests that early-stage material control directly influences end-product usability. This outcome confirms that preventive QC integration enhances not only procedural accuracy but also user-oriented product performance.

Based on a broader TVET policy perspective, the results reinforce the argument that industry-linked curriculum design is essential in mitigating skills mismatch (Kebede et al., 2024). Earlier research frequently conceptualized industry collaboration at the macro level through internships or partnerships, without embedding industry standards into classroom pedagogy. The present model internalizes industrial inspection systems into daily workshop practice. This internalization reflects a micro-level implementation of industry alignment, thereby addressing the structural gap identified in the Introduction. Consequently, the findings move beyond confirming PjBL effectiveness and demonstrate how quality governance mechanisms amplify vocational authenticity. The novelty of this research becomes evident through comparative positioning. While previous studies documented cognitive and psychomotor improvements in STEAM-based vocational settings, they did not employ a structured three-stage QC framework tied to measurable product standards (Ekayana et al., 2025; Rahim et al., 2024). Similarly, meta-analytical evidence on STEM–PBL effectiveness has highlighted moderate-to-high learning gains but has not reported effect sizes associated with industrial inspection integration (Cheng & Kinoshita, 2024). The present study contributes a new conceptual synthesis in which QC is not treated as a post-project evaluation but as an embedded, continuous pedagogical scaffold. This structural embedding distinguishes the proposed model from prior PjBL–STEAM approaches and explains the amplified effect size observed.

Theoretically, this study advances vocational learning theory by integrating constructivist project-based pedagogy with industrial quality management principles. Authentic project environments have been shown to enhance learning relevance; however, authenticity also requires alignment with real production constraints (Chistyakov et al., 2023). The integration of inspection-based QC introduces such constraints in a structured manner. This synthesis expands the conceptual boundaries of STEAM by embedding industrial accountability within interdisciplinary learning. Hence, the contribution is both pedagogical and managerial: it demonstrates that quality assurance functions as a cognitive and procedural regulator in vocational education.

In terms of generalization, the findings suggest that vocational disciplines characterized by measurable production outputs, such as woodworking, welding, manufacturing, and construction, may benefit from embedding structured QC frameworks into project-based curricula. The model is particularly transferable to contexts where product standards are explicitly defined and industry compliance is critical. Although replication across diverse vocational domains is necessary to validate broader applicability, the present evidence indicates that inspection-based QC integration strengthens learning effectiveness and industry readiness simultaneously. Overall, the discussion reaffirms that the gap identified in the Introduction, namely the absence of systematic QC leading to substandard product quality, has been empirically addressed. The integration of PjBL–STEAM with structured inspection-based QC not only improves cognitive achievement but also elevates product quality to industry-aligned standards. This dual impact positions the model as a theoretically grounded and empirically validated innovation in contemporary vocational education.

5. Conclusion

This study confirms that the integration of Project-Based Learning (PjBL) with a STEAM approach and a structured three-stage inspection-based Quality Control (QC) system significantly enhances cognitive achievement and measurable product quality in vocational woodworking education. The findings demonstrate not only high learning gains but also substantial improvements in finishing, structural strength, aesthetics, and functionality, thereby narrowing the previously identified gap between student outputs and industry benchmarks. The principal novelty of this research lies in embedding inspection-based QC, comprising incoming, in-process, and final inspections, into the core instructional design of PjBL–STEAM. Unlike previous STEAM-based vocational studies that focused primarily on multidomain competencies, this study positions QC as a continuous formative scaffold that regulates precision, accountability, and iterative refinement throughout the production cycle. This reconceptualization advances vocational pedagogy by integrating constructivist project-based learning with industrial quality governance principles. The proposed model provides a theoretically grounded and empirically validated framework for aligning vocational education with industry standards, thereby strengthening graduate readiness and workforce relevance.

Author's declaration

Author contribution

Fani Keprila Prima: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Writing – original draft, Visualization, Project administration. **Rijal Abdullah:** Methodology, Validation, Investigation, Formal analysis, Writing – review & editing. **Juniman Silalahi:** Investigation, Resources, Data curation, Validation, Writing – review & editing. **Ari Syaiful Rahman Arifin:** Methodology, Supervision, Validation, Writing – review & editing. **Trimailuzi:** Supervision, Conceptualization, Funding acquisition, Project administration, Writing – review & editing.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Ethical clearance

Permission to conduct this study was obtained from the Dean of the Faculty of Engineering, Universitas Negeri Padang, and the Head of the Civil Engineering Department. The study was conducted in accordance with institutional policies and the ethical principles of educational research. All participants were informed about the purpose and procedures of the study, participation was voluntary, informed consent was obtained prior to data collection, and the confidentiality of participants' information was maintained throughout the research.

AI statement

The authors used artificial intelligence (AI)-assisted language tools solely to improve the grammar, language quality, and readability of the manuscript. All scientific content, including the study design, data collection, data analysis, interpretation of the results, conclusions, figures, and tables, was created entirely by the authors. No text, figures, tables, or other research content were generated by AI. The authors carefully reviewed and took full responsibility for the final version of the manuscript.

Publisher's and Journal's note

Universitas Negeri Padang as the publisher, and the Editor of Jurnal Pendidikan Teknologi Kejuruan state that there is no conflict of interest towards this article publication.

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