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Enhancing Higher-Order Thinking and Conceptual Understanding through STEM-PjBL: A Comprehensive Assessment of Its Impact on Education

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Abstrak

Pendidikan STEM (Science, Technology, Engineering, and Mathematics) sering menghadapi kesulitan dalam mengembangkan keterampilan berpikir tingkat tinggi siswa dan mengatasi miskonsepsi konseptual yang berkelanjutan. Untuk mengatasi tantangan ini, pendekatan pendidikan inovatif seperti STEM-PjBL (Project-Based Learning) sangat penting untuk meningkatkan hasil belajar siswa. Penelitian ini bertujuan untuk menilai secara kritis dampak STEM-PjBL terhadap keterampilan berpikir tingkat tinggi siswa, mengevaluasi efektivitas model seperti Ethno-STEM dan Modul Fisika STEM-PjBL dalam mengurangi miskonsepsi dan meningkatkan pemahaman konseptual, serta merumuskan rekomendasi strategis untuk mengintegrasikan STEM-PjBL ke dalam kurikulum pendidikan STEM. Penelitian ini menggunakan tinjauan literatur sistematis yang dikombinasikan dengan meta-analisis, yang mengikuti pedoman PRISMA. Desain penelitian mencakup pencarian dan evaluasi kritis yang ketat terhadap studi-studi terbaru yang bersumber dari database akademik terkemuka, termasuk Web of Science, Scopus, Science Direct, dan Google Scholar, dengan pencarian terbaru dilakukan pada 10 Januari 2024. Hasilnya menunjukkan bahwa STEM-PjBL secara signifikan meningkatkan keterampilan berpikir tingkat tinggi, memperbaiki praktik dan teknik ilmiah, serta mendorong sikap ilmiah yang positif, sambil memperkaya keterampilan kognitif dan non-kognitif melalui integrasi elemen kewirausahaan dalam pembelajaran STEM. Temuan ini menekankan pentingnya memasukkan STEM-PjBL ke dalam kurikulum pendidikan untuk lebih mempersiapkan siswa menghadapi karier masa depan yang kompleks dan meningkatkan kualitas keseluruhan pendidikan. Implementasi STEM-PjBL di kelas dapat membantu mempersiapkan siswa menghadapi tantangan di bidang STEM, dengan memberi mereka keterampilan yang relevan untuk sukses. Studi ini memberikan wawasan penting tentang potensi STEM-PjBL untuk memperkuat kompetensi siswa dan meningkatkan efektivitas kurikulum STEM.

***Kata kunci*:** Project-Based Learning, STEM-PjBL, Systematic Literature Review

Abstract

STEM (Science, Technology, Engineering, and Mathematics) education often struggles to develop students' higher-order thinking skills and to address persistent conceptual misconceptions. To overcome these challenges, innovative educational approaches like STEM-PjBL (Project-Based Learning) are crucial for enhancing student learning outcomes. This study aims to critically assess the impact of STEM-PjBL on students' higher-order thinking skills, evaluate the effectiveness of models such as Ethno-STEM and STEM-PjBL Physics Modules in reducing misconceptions and improving conceptual understanding, and formulate strategic recommendations for integrating STEM-PjBL into STEM education curricula. The research employs a systematic literature review combined with meta-analysis, following PRISMA guidelines. The study design includes a rigorous search and critical evaluation of recent studies sourced from leading academic databases, including Web of Science, Scopus, ScienceDirect, and Google Scholar, with the latest search conducted on January 10, 2024. The results show that STEM-PjBL significantly enhances higher-order thinking skills, improves scientific practices and techniques, and fosters positive scientific attitudes, while also enriching cognitive and non-cognitive skills through the integration of entrepreneurial elements in STEM learning. These findings highlight the importance of incorporating STEM-PjBL into educational curricula to better prepare students for complex future careers and to improve overall educational quality. Implementing STEM-PjBL in the classroom can help equip students with the relevant skills needed for success in STEM fields. This study provides valuable insights into the potential of STEM-PjBL to strengthen student competencies and enhance the effectiveness of STEM curricula.

Keywords: Project-Based Learning, STEM-PjBL, Systematic Literature Review

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1. INTRODUCTION

Project-based learning is recognized as a promising strategy for enhancing student learning outcomes in higher education (Bakri et al., 2023; Guo et al., 2020). The ideal

conditions for STEM (Science, Technology, Engineering, and Mathematics) education involve high student engagement, deep understanding, and effective integration of technology with project-based methods. However, traditional learning methods still dominate, with teachers serving as "conveyors of knowledge" and students as "recipients of information," which hinders the achievement of desired skills (Mustafa et al., 2016; Saraç, 2018). This gap highlights the urgent need for innovative approaches in STEM education. STEM education can enhance the quality of human resources through an interdisciplinary approach that prepares students for their future careers (Martín-Páez et al., 2019; Maryanti et al., 2022). Modifying and combining STEM with learning models can improve implementation and instruction effectiveness.

STEM-PjBL, which integrates STEM subjects into project-based learning, offers a solution to this gap by enhancing student engagement and facilitating deeper understanding (Astuti et al., 2019; Wahono et al., 2020). Research shows that combining STEM with project-based learning can improve academic achievement, motivation, and problem-solving skills (Bybee, 2010; Chasanah et al., 2022; Wu & Anderson, 2015). Nevertheless, the implementation of this approach often lacks coherence and is not comprehensive across various educational contexts, necessitating further exploration of its effectiveness and application (Bosman & Fernhaber, 2019; Chiang & Lee, 2016). STEM project-based learning is an instructional model designed to meet the needs of STEM education and prepare students for technological advancements, this model integrates Science, Technology, Engineering, and Mathematics (STEM) into curriculum design (Alibraheim & El-Sayed, 2021; Hsiao et al., 2010). This assertion is acceptable given PjBL characteristics are like the integrated STEM approach (Hamad et al., 2022; Siew et al., 2015).

Based on the theoretical framework for STEM-PjBL development, this study systematically reviews the existing literature to assess the significant advancements and gaps in this educational approach. STEM-PjBL, or STEM-based Project-Based Learning, represents a crucial pedagogical strategy aimed at equipping students with the skills necessary to thrive in STEM fields. This approach directly responds to the growing demand for educational practices that develop higher-order thinking skills, problem-solving abilities, and a strong conceptual understanding among students (Bandjar et al., 2024; Handayani & Wulandari, 2021). STEM-PjBL emphasizes active learning through real-world projects that integrate science, technology, engineering, and mathematics disciplines. By engaging students in meaningful, interdisciplinary tasks, this method promotes critical thinking and collaborative problem-solving, which are vital for success in modern STEM-related careers (Admawati & Jumadi, 2021; Handayani & Wulandari, 2021). The literature highlights various innovative implementations of STEM-PjBL, demonstrating its potential to transform classroom dynamics and enhance student engagement.

Despite these advancements, there remain significant gaps in understanding the broader impact of STEM-PjBL across diverse educational contexts. The effectiveness of this approach often depends on factors such as teacher preparedness, resource availability, and alignment with curriculum standards (Admawati & Jumadi, 2021; Bakri et al., 2023). Furthermore, disparities in access to STEM-PjBL opportunities can exacerbate educational inequities, particularly in under-resourced schools or regions. Given the global emphasis on preparing students for complex and rapidly evolving STEM careers, it is imperative to evaluate how STEM-PjBL has been implemented across different settings. Comprehensive analysis of these implementations can provide insights into best practices, highlight areas requiring further research, and inform policymakers and educators seeking to optimize this approach (Admawati & Jumadi, 2021; Chen & Lin, 2019). This study seeks to contribute to this ongoing discourse by examining the successes, challenges, and potential of STEM-PjBL in fostering 21st-century competencies among students.

To reveal the cumulative progress made in research over the past decade, the aims of this study is to assess the impact of STEM-PjBL on students' higher-order thinking skills, evaluate the effectiveness of models such as Ethno-STEM and STEM-PjBL physics modules in reducing misconceptions and improving conceptual understanding, and formulate strategic recommendations for integrating STEM-PjBL into STEM education curricula. The urgency of this topic lies in its potential to shape the future of STEM education, ensuring that it meets the demands of a rapidly changing technological landscape.

2. METHODS

We conducted a thorough literature review to uncover the current state of research on the advancement of knowledge on STEM-PjBL integration in mathematics learning. This approach involves "a review of a clearly formulated question that uses systematic and explicit methods to identify, select, and critically appraise relevant research, and to collect and analyze data from the studies that are included in the review". The latest guidelines for Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) were used in this review (Page et al., 2021). The following databases received the latest search results on January 10, 2024: (1) Web of Science (WoS) Core Collection, (2) Scopus, Science Direct and google Scholar. These databases are internationally recognized for their high indexing standards. There is also a lot of research in the field of education science, especially mathematics education. Search strings with Boolean operators and asterisks were used in the systematic review to capture relevant research in the field of mathematics education research, as shown in Table 1.

Table 1. Search Strings

Data Base	Search Term
WoS (Core Collection)	TOPIC: (STEM-PjBL AND math) Refined by: WEB OF SCIENCE CATEGORIES: (Education Educational Research OR Mathematics OR Education Scientifc Disciplines OR Education Special) AND LANGUAGES: (English) AND DOCUMENT TYPES: (Article OR Book Chapter OR Review OR Early Access OR Proceedings Paper)
Scopus	TITLE-ABS-KEY (stem-pjbl) Refned by: (LIMIT-TO (SUBJAREA, "SOCI") OR LIMIT-TO (SUBJAREA, "MATH") AND (LIMIT-TO (LANGUAGE, "English") (Document type: Conference paper, Article)
Science Direct	Find articles with these terms: STEM-PjBL
Google Scholar	Google Cendekia: STEM-PjBL

The current survey focuses on scholarly studies published in English in the domain of mathematics education that are related in depth to the concept, measurement, or attempt to influence STEM-PjBL learning. The inclusion and exlusion criteria are show in Table 2.

Table 2. Inclusion and Exclusion Criteria

Inclusion Criterion (IC)	Exclusion Criterion (EC)
IC1: Studies conducted at every level of mathematics education	EC1: Non-mathematical studies and education

Inclusion Criterion (IC)	Exclusion Criterion (EC)
IC2: The study focuses on conceptualization, measurement, impact, or influence of implementing STEM-PjBL learning on students' skills and abilities in school or higher education	EC2: Research does not examine the conception, assessment, impact, or influence of STEM-PjBL learning. $EC2_1$: Studies not focusing on the conceptualization, measurement, or fostering of STEM-PjBL learning. $EC2_2$: Studies mentioning the conceptualization, measurement, or fostering of STEM-PjBL learning, but not focusing on them
IC3: Studies published in English	EC3: Studies not published in English
IC4: Document types: journal articles, reviews, book chapters, or proceedings papers	EC4: Document types: editorials, whole books, book reviews, and notes
IC5: Studies indexed in Web of Science Core Collection, Scopus, Taylor & Francis Online Journals, Google Scholar	EC5: Studies not indexed in any database included in IC5

Across all arithmetic education levels and did not place restrictions on how long the findings may be published. To decide which papers were eligible for evaluation, we employed five inclusion criteria in addition to the inclusion and exclusion criteria listed in Table 2. We divided the exclusion and exclusion criteria since not all the exclusion criteria matched the inclusion criteria. It was the duty of each author in this study to make sure the papers qualified for inclusion. Diagram of the manuscript selection process is show in Figure 1.

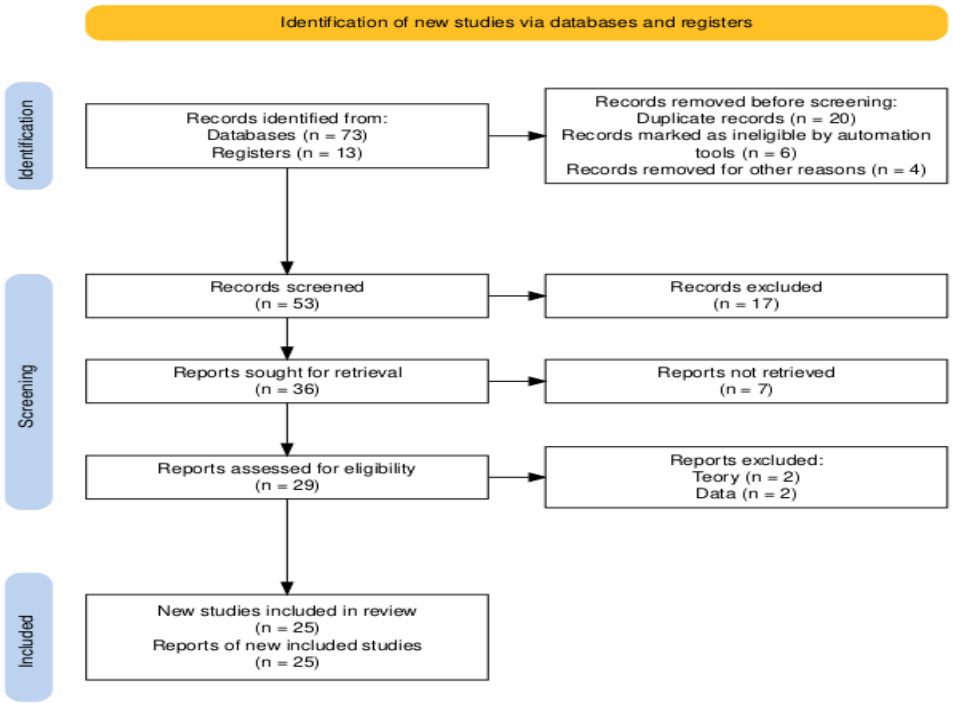

Figure 1. Flow Diagram of the Manuscript Selection Process

Our analysis involved 25 review papers, primarily consisting of screening and coding procedures. The first step was to screen the eligible studies and conduct an in-depth

examination. Then, a coding scheme was developed, and the codes were organized into two main categories according to our research questions: Characteristics of the studies and research methodologies and how does the development of STEM-PjBL enhance student abilities? This analysis was conducted using qualitative content analysis methods according to (Miles et al., 1994), focusing on the topics discussed in the reviewed studies. We grouped the general characteristics of the reviewed studies and the research methodologies used based on ten sub-categories: year of publication, type of document, geographical distribution, research methods, sample/participants, educational level of participants, sample size, prior experience in STEM-PjBL, types of tasks and projects in STEM-PjBL, and data collection methods. We analyzed the theoretical frameworks used for STEM-PjBL that underpinned these studies.

The initial coding was performed by the first author, and we employed several strategies to ensure coding reliability. First, we re-coded all studies after a four-week interval, resulting in a high consistency rate between the two coding sessions. Second, we randomly selected 20% of the reviewed papers to be re-examined by another coder with experience in qualitative data analysis. The inter-coder reliability was found to be very high. Third, the first and second authors separately coded the theoretical frameworks of all included studies. After discussing the coding discrepancies, we reached a full consensus. These strategies demonstrate that our coding system is reliable.

3. RESULTS AND DISCUSSION

Results

Types of Documents and Publication Years

Our analysis of the literature on STEM-PjBL involved 25 papers, including 9 empirical studies, 12 theoretical studies, 1 survey or review study, and 3 document analysis studies, all published as journal articles. The results indicate a lack of consistent progression over time in the number of publications, suggesting that research contributions on this topic fluctuate rather than show a stable upward trend. This variability highlights the need for more sustained research efforts in this field. Annual number of studies on STEM-PjBL is show in Figure 2.

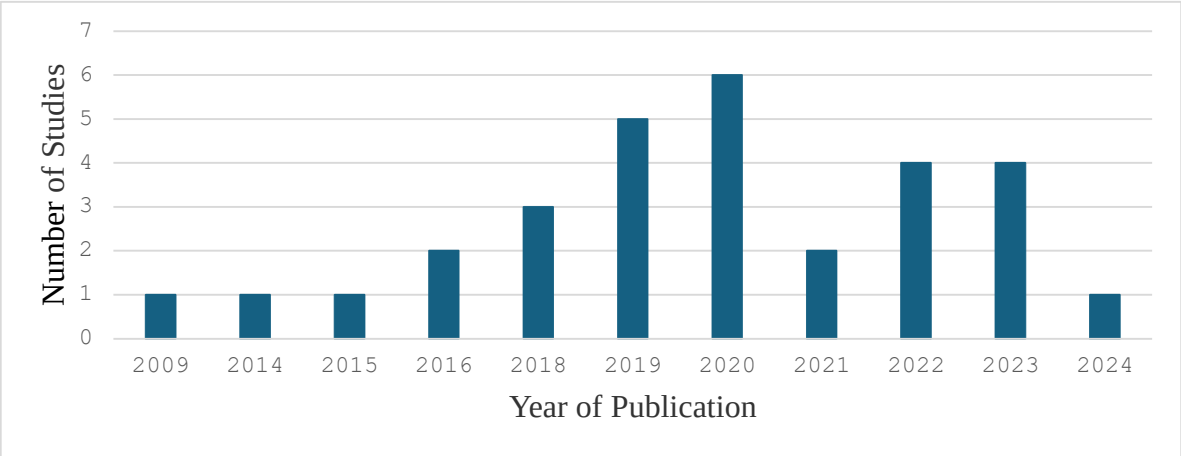

Figure 2. Annual Number of Studies on STEM-PjBL

The research methods employed across these studies varied significantly. Empirical studies, which focus on collecting and analyzing real data, represented 36% of the total papers. In contrast, theoretical studies, which develop and evaluate theories and concepts, made up nearly half of the papers at 48%. Notably, only one study was a survey or review, indicating that literature reviews are less common compared to empirical and theoretical research. Additionally, three studies used document analysis as their primary method, illustrating the use of written documents as a data source. The predominance of journal articles underscores the importance of formal academic dissemination. The distribution of research methods is show in Figure 3.

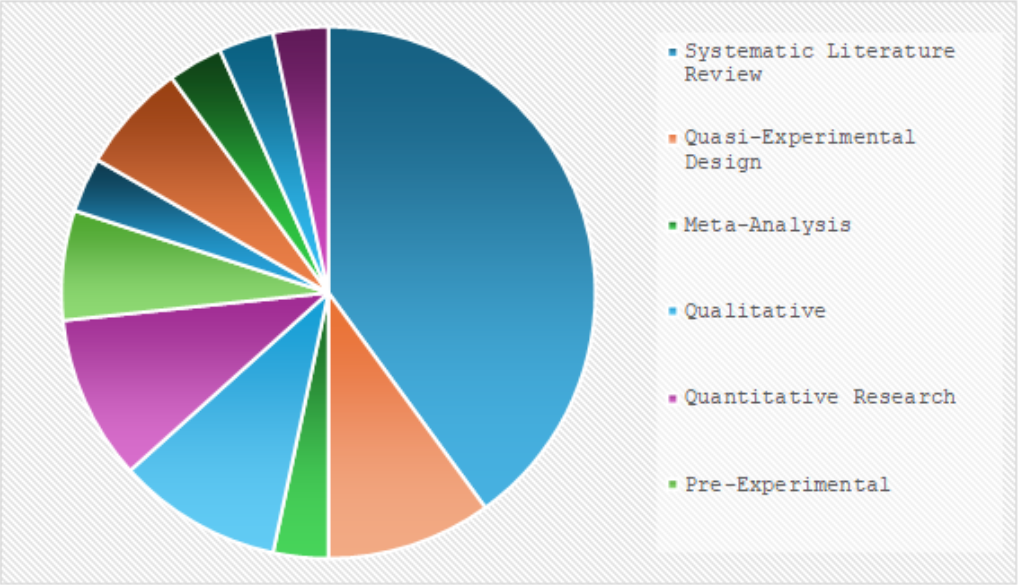

Figure 3. Distribution of Research Methods

Geographic Distribution

Geographically, the studies reveal a diverse range of contributions from different countries, with notable variations in research cultures. Researchers from Asia, particularly Indonesia, made significant contributions, followed by those from Europe. The differences in research focus reflect regional priorities; for example, European studies emphasize competency concepts, while Asian and American studies focus more on skills. Authors' countries of affiliation is show in Table 3.

Table 3. Authors' Countries of Affiliation

Continent	Country	n
Europe	England	1
	Netherlands	1
	United Arab Emirates	1
	Granada	1
Asia	Malaysia	4
	Turkey	2
	Indonesia	10
	Taiwan	2
	China	1
North America	USA	2

The reviewed studies utilized various data collection methods, with interviews being the most frequently employed technique. Many studies used multiple methods rather than relying on a single approach. However, the specification of instruments was often lacking, especially in literature reviews. Some studies did not strictly evaluate STEM-PjBL but also explored related aspects such as attitudes or beliefs. The integration of the Ethno-STEM-Project-Based Learning Model has proven effective in enhancing students' higher-order thinking skills and reducing misconceptions, particularly in contexts such as activities around Lake Tempe. Similarly, the STEM-PjBL Physics Module has significantly improved students' real-world connections and conceptual understanding, as demonstrated in recent studies from Malaysia and Korea. Data collection methods used in the reviewed studies is show in Figure 4.

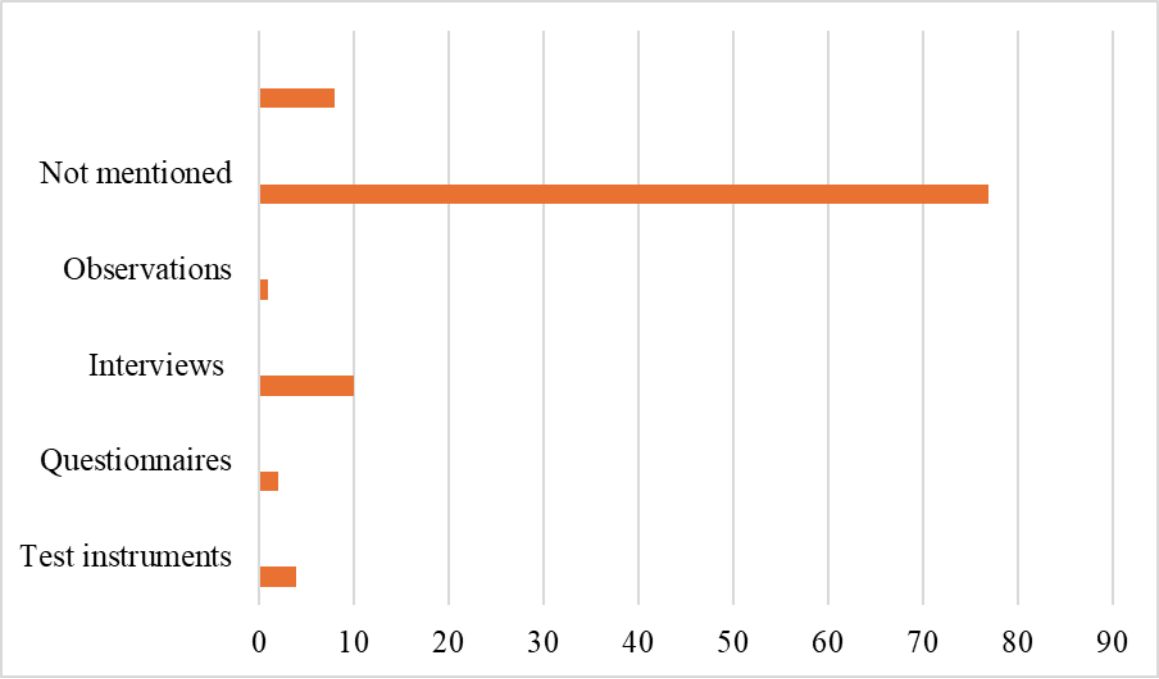

Figure 4. Data Collection Methods used in the Reviewed Studies

The implementation of STEM-PjBL also positively impacts students' scientific practices, techniques, and attitudes, reinforcing skills in planning investigations and conducting inquiries. The integration of entrepreneurial practices in STEM education, through competency-based approaches, has enhanced both cognitive and non-cognitive competencies among high school students. The use of drones in STEM education has increased career awareness and student engagement, developing collaborative problem-solving skills. Despite these advances, challenges remain in assessment and evaluation, with a need for practical tools and teacher guidelines. The growing interest in STEM education research underscores the importance of innovative approaches to equip students with essential skills for the modern era.

Discussion

In addressing the research question on how STEM-PjBL developments enhance students' abilities, findings from several studies indicate that this approach yields significant positive impacts. For instance, the Ethno-STEM-Project-Based Learning Model has proven effective in enhancing students' higher-order thinking skills and reducing their misconceptions about physics concepts while linking conceptual understanding to student

environmental phenomena (Admawati & Jumadi, 2021; Eltanahy et al., 2020; Martawijaya et al., 2023). These results suggest that integrating cultural elements into STEM-PjBL can contextualize learning, making abstract concepts more tangible and relatable for students, which is crucial in improving comprehension and reducing learning gaps (Martawijaya et al., 2023; Sulaiman et al., 2024).

Furthermore, the integrated STEM-PjBL Physics Module consistently enhances students' real-world and conceptual connections, as well as deepening their applied conceptual understanding, as seen in research outcomes in Malaysia and Korea (Sulaiman et al., 2024; Sumardiana et al., 2019). These findings underscore the importance of STEM-PjBL in fostering a holistic understanding of scientific concepts, which not only prepares students for academic success but also equips them with practical skills needed to navigate complex real-world problems (Sattar & Nawaz, 2024; Yeung et al., 2024). STEM-PjBL also helps improve students' scientific practices, techniques, and scientific attitudes, with significant enhancements in investigative skills and strong scientific attitudes (Admawati & Jumadi, 2021; Hidayat, 2021). The improvement in these areas indicates that STEM-PjBL is effective in promoting a more inquiry-based learning environment, where students actively engage in the scientific process, thereby fostering a deeper understanding of scientific principles and developing critical thinking skills. The M-STEM-PjBL course provides students with authentic hands-on learning experiences that enhance their skills, creativity, and confidence (Guo et al., 2020; Liebech-Lien & Sjølie, 2021; Wahono et al., 2020).

The integration of entrepreneurial practices in STEM education has resulted in innovative approaches that enrich both cognitive and non-cognitive competencies among students (Eltanahy et al., 2020; Sari & Afriansyah, 2022). These approaches not only prepare students for the workforce by enhancing their problem-solving and critical thinking skills but also encourage creativity and innovation, which are essential competencies in today’s rapidly changing job market. The development of research and the number of readers in the International Journal of STEM Education from 2014 to 2018 demonstrate a growing interest and advancement in STEM education research, particularly in K-12 teaching and learning (Chen & Lin, 2019; Li et al., 2019).

The findings from this research contribute significantly to the growing body of literature on STEM education by demonstrating that STEM-PjBL is a versatile approach that can be adapted to various educational contexts, including those that incorporate cultural elements or focus on real-world applications. The implications of this study are far-reaching, suggesting that educators and policymakers should consider adopting STEM-PjBL as a core instructional strategy to better prepare students for future challenges. This approach not only aligns with current educational goals of fostering 21st-century skills but also provides a framework for integrating interdisciplinary learning and promoting lifelong learning habits.

One of the key advantages of this study is its comprehensive approach to evaluating STEM-PjBL across different contexts, providing robust evidence of its effectiveness in enhancing various student competencies. However, the study is limited by its reliance on specific case studies, which may not be generalizable to all educational settings. Future research should explore the scalability of STEM-PjBL and investigate its impact on a broader range of student populations. Future researchers are encouraged to explore the long-term effects of STEM-PjBL on student outcomes, particularly in diverse educational environments. Additionally, further investigation into the integration of entrepreneurial skills within STEM education is warranted, as this could provide valuable insights into how to better prepare students for the demands of the modern workforce.

4. CONCLUSION

This study demonstrates that the implementation of STEM Project-Based Learning (STEM-PjBL) significantly enhances various aspects of students' abilities in STEM education. Based on the review of models such as Ethno-STEM-PjBL and Integrated STEM-PjBL Physics Modules, it was found that this approach effectively develops higher-order thinking skills, reduces conceptual misunderstandings, and deepens students' conceptual understanding. Additionally, STEM-PjBL has been shown to improve students' scientific practices, techniques, and attitudes, as well as enrich cognitive and non-cognitive skills through the integration of entrepreneurial practices in STEM learning. These findings support the effectiveness of STEM-PjBL as a relevant and beneficial learning strategy in the context of modern education. By linking learning to real-world experiences and collaborative projects, STEM-PjBL not only prepares students to master academic content but also to develop the skills necessary for success in future STEM careers. Therefore, the implementation of STEM-PjBL in educational curricula is expected to be continuously supported and expanded to maximize benefits for the global development of STEM education.

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