



# Effects of Project-Based Learning, STEM Education, and Culture-Based Learning on K-12 Mathematics Achievement: A Meta-Analysis

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## ABSTRACT

**Purpose:** This study evaluates and compares the effectiveness of Project-Based Learning (PjBL), STEM/STEAM, and Culture-Based Learning (CBL) on students' mathematics achievement to address fragmented findings in existing literature. **Methods:** A systematic review and meta-analysis following PRISMA guidelines was conducted on 34 empirical studies published between 2015 and 2025 across four major academic databases: Scopus, ERIC, ScienceDirect, and Sinta. Effect sizes were calculated using Cohen's  $d$  and analyzed with a random-effects model. **Findings:** All three student-centered approaches significantly improve mathematics achievement, with a large pooled effect size ( $d = 0.99$ ). Subgroup analysis revealed that CBL yielded the highest effect size ( $d = 1.50$ ), followed by STEM/STEAM ( $d = 1.07$ ), and PjBL ( $d = 0.74$ ). High heterogeneity indicates effectiveness is heavily influenced by contextual implementation factors. **Research Implications:** The findings recommend that educators and curriculum developers integrate contextual, project-based, and interdisciplinary approaches to enrich mathematics learning and bridge abstract concepts with students' real-world experiences. **Originality:** This research provides a unique contribution by systematically comparing the relative strengths of PjBL, STEM/STEAM, and CBL within a single analytical framework, demonstrating the strong potential for an integrated hybrid pedagogical model in mathematics education.



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## INTRODUCTION

The increasingly rapid development of the modern era demands individuals to possess essential 21st-century competencies. These competencies include critical thinking, creativity, collaboration, communication, as well as digital literacy and data-driven decision-making (Herlinawati et al., 2024; Martínez-Bravo et al., 2022). Mathematics plays a crucial role as a medium for developing these skills. However, findings from educational assessments and research indicate that students' mathematics achievement remains relatively low or stagnant. According to the 2022 Programme for International Student Assessment (PISA), Indonesian students achieved an average mathematics score of 366, which is significantly below the overall average score of 472 (OECD, 2023).

One of the contributing factors to low mathematics achievement is teacher competence (Yang & Kaiser, 2023), particularly in managing the learning process. Teachers who are not optimal in selecting instructional approaches, strategies, and learning media tend to implement procedural and less contextual learning. As a result, students experience difficulties in developing deep conceptual understanding and in connecting mathematical concepts to real-life situations. Therefore, a fundamental shift in educational paradigms is necessary, moving from rote learning toward meaningful learning that connects theoretical concepts with practical applications.

Various pedagogical approaches have evolved, offering innovative learning models that place students at the center of learning activities (student-centered). Three models that have gained widespread attention in the last decade are Project-Based Learning (PjBL), Science, Technology, Engineering, and Mathematics (STEM), and Culture-Based Learning (CBL). Theoretically, the implementation of PjBL, STEM, and CBL is believed to improve mathematics achievement because it engages students not only cognitively but also affectively through solving problems relevant to their lives. Project-Based Learning (PjBL) is considered effective in fostering collaboration and problem-solving

skills through project-based learning experiences (Meng et al., 2023; Rehman et al., 2023). The STEM/STEAM (Science, Technology, Engineering, Arts, and Mathematics) approach emphasizes cross-disciplinary integration to train creativity and systemic thinking (Aguilera & Ortiz-Revilla, 2021; Juškevičienė et al., 2021; Marín-Marín et al., 2021). Meanwhile, Culture-Based Learning (CBL) has increasingly been highlighted as an essential strategy to make learning more relevant to students' social and cultural contexts (Komalasari et al., 2018; Smith et al., 2022).

Although each of these approaches presents distinct pedagogical advantages that will be further detailed in the literature review, the empirical findings regarding their effectiveness remain fragmented. Several meta-analyses conducted in the last five years have focused on each approach separately. For instance, Ayari et al. (2025) limited their review to Problem-Based Learning, while Alibek & Akhmetova (2025) focused exclusively on STEM in early childhood education. Similarly, Megawati (2024) examined the integration of STEM-PjBL in the context of biology practical skills. These studies do not provide a comprehensive comparison of the relative effectiveness of the three approaches within a single analytical framework. This condition creates challenges for educators and policymakers in determining the most effective instructional approach for mathematics learning.

In practice, PjBL and STEM often share overlapping characteristics and are frequently integrated (Wahono et al., 2020), whereas CBL is often implemented separately. This suggests that the selection of instructional approaches is frequently based on subjective preferences rather than on a synthesis of strong empirical evidence. Consequently, the implementation of these approaches in classrooms varies widely and often faces significant challenges in consistency (Sánchez-García & Reyes-de-Cózar, 2025). Therefore, a comparative study is needed not only to examine the effectiveness of each approach but also to systematically compare their relative strengths.

Based on this rationale, the present study aims to evaluate and compare the effectiveness of Project-Based Learning, STEM, and Culture-Based Learning on mathematics achievement through a meta-analysis approach. Specifically, this study aims to address the following research questions. (1), What is the overall effect size of implementing PjBL, STEM, and CBL on students' mathematics achievement?, (2) How do the effect sizes of PjBL, STEM, and CBL compare to one another within a single analytical framework?, (3) To what extent does heterogeneity exist among the reviewed studies, and what are the implications for developing an integrated pedagogical model?.

## LITERATURE REVIEW

### Project-Based Learning (PjBL)

Project-Based Learning (PjBL) is a learning method based on practical experience (Lavado-Anguera et al., 2024), where students explore a topic through the investigation and completion of complex, relevant, and authentic projects (Boardman et al., 2024; Thomas, 2000; Yusri et al., 2024). Theoretically, PjBL is rooted in constructivism and John Dewey's experiential learning philosophy, which emphasizes the "Learning by doing" principle (Malik & Behera, 2024). Through this process, students are given the autonomy to explore driving questions (Miller et al., 2025), construct knowledge, and develop 21st-century skills such as critical thinking, problem-solving, communication, and collaboration (Al-Kamzari & Alias, 2025). Learning outcomes are manifested in the form of tangible products, presentations, or solutions.

PjBL consistently proves effective in developing various higher-order thinking skills required in the 21st century, including critical thinking, problem-solving abilities, and collaboration skills (Jiménez-Gaona & Vivanco-Galván, 2024; Rehman et al., 2024). Furthermore, PjBL positively impacts student engagement, positive attitudes, and self-efficacy in mathematics learning (Cruz et al., 2022; Rijken & Fraser, 2024). Cruz et al. (2022) further reported that PjBL contributes to improved academic achievement.

Common barriers to implementation include time constraints, limited resources, and a lack of teacher training and readiness, all of which impact effectiveness (Batysheva & Kitbayeva, 2022; Dewi, 2022). Furthermore, PjBL requires complex preparation, relatively high costs, and is often not aligned with standardized assessment systems that emphasize content coverage rather than depth (Chao et al., 2025; Saavedra & Rapaport, 2024). The evaluation of learning outcomes is also challenging due to the subjective nature of project outputs, while institutional support is often inadequate (Adnan & Rahman, 2024). Cross-disciplinary studies, including those integrating cultural aspects, indicate additional challenges such as designing authentic project experiences, managing workload, and balancing student satisfaction expectations (Meng et al., 2023; Miao et al., 2024).

### STEM/STEAM

STEM/STEAM is a learning approach that integrates multiple disciplines (Science, Technology, Engineering, Art, Mathematics). The STEM concept was first developed by the National Science Foundation (NSF) in the United States in the early 1990s under the acronym SMET (Bybee, 2013; Hallinen, 2025). As it evolved, this approach expanded

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into STEAM by incorporating elements of "Arts," aiming to balance creativity, aesthetics, and the humanities with science and technology (Marin-Marín et al., 2021). The disciplines of Science, Technology, Engineering, Art, and Mathematics are viewed as crucial fields that need holistic development to shape an adaptive, innovative generation capable of addressing real-world complexities (Okwara & Pretorius, 2023).

The STEM/STEAM approach offers several advantages that significantly contribute to the development of students' 21st-century skills, including critical thinking, creativity, innovation, collaboration, and problem solving (Bybee, 2013; Izzati et al., 2019). According to Holmlund et al. (2018), STEM/STEAM makes learning more relevant to real-world contexts, encourages innovation, and prepares students to address contemporary issues related to economics, environment, energy, and health. The inclusion of the Arts dimension enhances students' aesthetic awareness and holistic skill development, increases motivation and engagement, and supports multiple intelligences, while also contributing to improved academic achievement (Aguilera & Ortiz-Revilla, 2021; Hughes et al., 2022; Juškevičienė et al., 2021; Videla et al., 2021).

The implementation of the STEM/STEAM approach is not without limitations and challenges. Saldívar-Almorejo et al. (2024) explain that applying STEM/STEAM faces challenges due to a gap between conventional teaching methods and digital learning needs, which creates technological, pedagogical, social, and institutional barriers. This approach requires teachers to possess interdisciplinary knowledge, the ability to integrate curricula, and strong classroom management skills; thus, it faces challenges related to limited teacher capabilities, time constraints, minimal training, lack of institutional support, and low community involvement, especially in developing countries (Aslam et al., 2023; K. Holmes et al., 2021; Le et al., 2021; Milara & Orduña, 2024). In practice, the integration of STEM/STEAM within a unified curriculum often fails to run smoothly and tends to become fragmented, following traditional learning patterns (Yang & Oh, 2024). The assessment of interdisciplinary skills also tends to face hurdles due to the lack of adequate instruments (Salvetti et al., 2023; S. Yang & Oh, 2024).

### **Culture-Based Learning (CBL)**

Culture-Based Learning (CBL) is an instructional approach that uses students' cultural perspectives as a framework for designing learning strategies (Au & Kawakami, 2012; Gay, 2018; UNESCO, 2015). Gay (2018) identifies five key components of CBL implementation: knowledge of students' cultural diversity, integration of culture into the curriculum, use of contextual teaching strategies, empathetic intercultural communication, and critical teacher reflection on personal biases. In mathematics education, this approach is reflected in ethnomathematics and culture-based mathematics learning, which aim to preserve and enrich students' cultural practices within the learning process (D'Ambrosio, 1985; Rigney et al., 2020).

Research indicates that Culture-Based Learning positively influences student engagement, sense of belonging, academic achievement, and social-emotional development across various educational contexts. Pagán (2022) found that CBL enhances student connectedness, teacher–student relationships, test performance, and critical awareness. Similar findings are reported in Montessori education, which aligns with CBL principles, where students from diverse backgrounds, including minority and low-income groups, demonstrate improved academic, social, and emotional outcomes, as well as reduced achievement gaps (Lillard et al., 2023). In Aboriginal education contexts, CBL implemented through culturally relevant pedagogy enhances cognitive and affective engagement and fosters positive student identity, while encouraging teachers to adopt reflective, inclusive, and culturally grounded practices (Rigney et al., 2020). In rural Ghana, culturally grounded approaches strengthen students' aspirations and school–family collaboration (Anlimachie et al., 2025).

However, the implementation of CBL also faces limitations. This approach often lacks systematic integration of science and technology and is rarely supported by well-structured project frameworks. In practice, teachers frequently encounter difficulties, resulting in superficial implementation that focuses only on cultural symbols without fundamentally transforming teaching methods (Caingcoy, 2023; Johnston & Green, 2024). In addition, limited knowledge and training hinder teachers' readiness to effectively integrate CBL (Coli et al., 2024; Susilo et al., 2025). Teachers may also experience uncertainty in distinguishing between cultural appreciation and inappropriate cultural appropriation (Nolan & Xenofontos, 2023). From a structural perspective, barriers include rigid curricula, conflicting school policies such as exclusive disciplinary systems and academic tracking, and systemic inequities that hinder the inclusive principles of CBL (Coli et al., 2024; Nolan & Xenofontos, 2023; Pagán, 2022). Furthermore, limited resources, lack of peer support, and insufficient parental and community involvement weaken the effectiveness of implementation (Pradhan et al., 2025).

## METHOD

This research is designed using a systematic review and meta-analysis following the updated guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) (Page et al., 2021). This approach was chosen for its ability to identify, evaluate, and synthesize empirical evidence systematically and comprehensively. The primary objective is to analyze the effectiveness of Project-Based Learning (PjBL), STEM/STEAM, and Culture-Based Learning (CBL) pedagogies within the context of mathematics education, which will subsequently serve as the foundation for formulating a hybrid meta-model conceptual framework.

### Literature Search

The literature search was conducted systematically across four major academic databases: Scopus, ERIC, ScienceDirect, and Sinta. To maintain relevance with current developments, the publication period was limited to the range of 2015 to 2025. This 10-year period was chosen because it marks an era where PjBL, STEM/STEAM, and CBL experienced rapid development and adoption in educational literature. The search strategy used a combination of main keywords:

*("Project-Based Learning" OR "PjBL") AND "Mathematics"*

*("STEM" OR "STEAM") AND "Mathematics"*

*("Culture" OR "Culture-Based Learning" OR "Culturally Responsive Teaching" OR "Ethnomathematics") AND "Mathematics"*

### Inclusion and Exclusion Criteria

The inclusion criteria for this study were as follows:

- 1) Peer-reviewed articles published in reputable international and national journals
- 2) Studies focusing on mathematics learning within K–12 education
- 3) Studies implementing one or more of the following approaches: Project-Based Learning (PjBL), STEM/STEAM, or Culture-Based Learning (CBL)
- 4) Empirical studies reporting sufficient quantitative data to calculate effect sizes (e.g., mean, standard deviation, p-values, or reported effect sizes)
- 5) Research designs including experimental, quasi-experimental, pre-experimental, or mixed-methods studies with quantitative results

The exclusion criteria included:

- 1) Non-empirical articles such as opinion papers, essays, editorials, or literature reviews
- 2) Studies conducted outside the context of mathematics education
- 3) Publications without full-text availability

### Study Selection Procedure

The study selection process followed the PRISMA 2020 flow diagram, consisting of four main stages: identification, screening, eligibility assessment, and final inclusion. The screening of titles, abstracts, and full texts was conducted independently by two researchers. Any disagreements regarding study eligibility were resolved through discussion until a consensus was reached. The inter-rater reliability for the study selection process was assessed using Cohen's kappa ( $\kappa = 0.85$ ), indicating strong agreement between the reviewers.

### Categorization of Hybrid Studies

Given that several studies implemented hybrid approaches (e.g., PjBL integrated with Ethnomathematics or PjBL combined with STEAM), a specific operational rule was established for categorization. Hybrid studies were assigned to a primary subgroup based on the dominant instructional framework explicitly emphasized in the study's primary research question, theoretical foundation, or core intervention design. Furthermore, a sensitivity analysis was considered to evaluate how the inclusion or exclusion of these hybrid studies impacted the pooled and subgroup effect sizes.

### Data Extraction

To obtain a comprehensive overview of the analyzed studies, data extraction was conducted for each article that met the inclusion criteria. Data extraction was independently performed by two coders using a standardized extraction instrument. Inter-rater reliability for the data extraction stage yielded a high percentage of agreement (92%). Discrepancies were resolved through a joint review of the original articles.

- 1) Author(s) and year of publication
- 2) Title of the study
- 3) Educational level of participants
- 4) Research design
- 5) Instructional approach (PjBL, STEM/STEAM, or CBL)
- 6) Measured dependent variables
- 7) Main findings or reported effect sizes
- 8) Country of origin

A complete summary of the 34 included studies is presented in Appendix A.

### Data Analysis

Effect sizes were computed using Cohen's *d*. Given the expected variability across studies, a random effects model was applied. For primary studies that did not report means and standard deviations, non-standard statistics (such as *F*-values, *t*-values, or *p*-values) were converted into Cohen's *d* using standard meta-analytic conversion formulas (Borenstein et al., 2010). Heterogeneity was assessed through the dispersion of effect sizes and formally evaluated using the  $I^2$  statistic and Cochran's *Q* test. Publication bias was examined using funnel plot inspection and Egger's regression test. All meta-analytic calculations, including the random-effects model, effect size computations, heterogeneity statistics, and Egger's test, were performed using IBM SPSS Statistics 26.0 software. In addition, descriptive analysis was conducted to identify trends in publication, geographic distribution, and educational levels. A complementary thematic synthesis was performed to examine patterns of pedagogical integration across PjBL, STEM/STEAM, and CBL

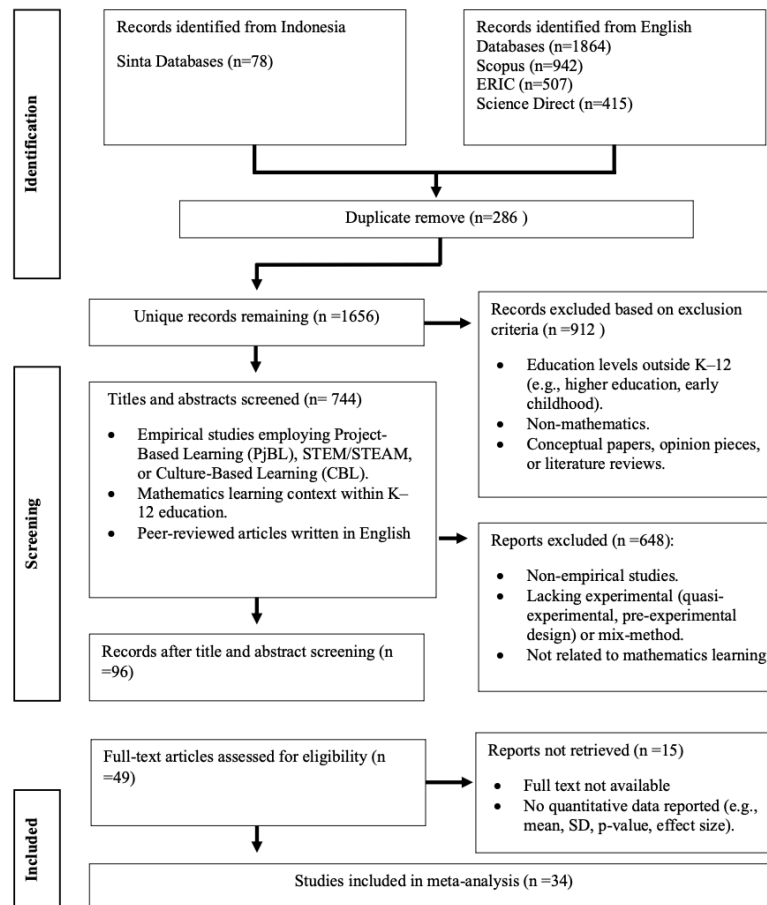


Figure. 1 PRISMA 2015 flow diagram revealing the inclusion–exclusion criteria for studies included in the meta-analysis

## RESULTS

### Research Trends

Analysis of the selected literature shows significantly different distribution patterns among the three approaches studied. This distribution reflects the evolution of research focus in mathematics education over the past decade.

#### 1. Project-Based Learning (PjBL)

Project-Based Learning (PjBL) is the most dominant approach in this database, with a total of 17 articles or 50 percent of all studies, showing relatively stable publication consistency from the start of the analysis period in 2015 to the present. The peak in publications occurred in 2024 with six articles specifically examining the effectiveness of PjBL in the context of post-pandemic recovery in rural areas and the integration of bilingual learning. Thematically, the focus of PjBL research has shifted from early studies emphasizing basic attitudes and achievement towards testing more complex 21st-century skills, especially creativity and mathematical problem-solving abilities.

#### 2. STEM/STEAM: Acceleration and Technology Integration

The STEM or STEAM approach contributed 10 articles or about 29 percent of the total data and showed very rapid growth in the last five years. Although STEM studies in this data began to appear formally in 2021, a significant surge in publications occurred in 2023 with five articles. Current trends in STEM research are characterized by strong integration of digital technology, such as the use of the Metaverse in the Meta-STEM concept and the use of Digital Learning Spaces to enhance student learning independence. Conceptually, research focus has also shifted from mere interdisciplinary integration towards issues of learning sustainability and the application of more structured instructional models, such as the 5E model (Engage, Explore, Explain, Elaborate, Evaluate).

#### 3. Culture-Based Learning (CBL): Rise of Contextual Focus

Although it has the smallest number of articles, seven or 21 percent of the total data, Culture-Based Learning (CBL) showed the most significant surge at the end of the analysis period, with 57 percent of the research published in 2025. This phenomenon indicates the increasing need for meaningful, contextual, and identity-based learning rooted in local culture as a response to the limitations of conventional approaches in motivating and engaging students. In the same period, a trend emerged towards integrating CBL with other models, particularly Project-Based Learning, as seen in the Ethnomathematics-Based PjBL approach, indicating a shift towards hybrid learning models. This trend confirms that PjBL remains a primary foundation due to its systematic and structured project framework, while CBL serves to strengthen relevance and meaning in learning through cultural context, thus complementing each other in meeting the demands of 21st-century learning.

### Geographical Distribution

#### 1. Dominance of Research in Indonesia

Indonesia is the main contributor in this meta-analysis, with a total of 18 articles or about 53 percent of all data. This contribution covers all three learning approaches: PjBL with seven articles, STEM with six articles, and CBL with five articles. This dominance reflects the active response of educational researchers in Indonesia to the direction of curriculum transformation that emphasizes project-based, contextual learning relevant to students' lives, including strengthening the integration of local culture through the ethnomathematics approach within CBL.

#### 2. Widest Geographical Spread of PjBL Approach

The Project-Based Learning approach shows the widest geographical spread compared to other approaches. Besides Indonesia, PjBL research was found in various regions: Turkey with two studies, Pakistan and the United States with two studies each, and Saudi Arabia, South Africa, Australia, and Colombia with one study each. This cross-continental spread indicates that PjBL has been globally adopted as a primary approach to improve conceptual understanding, achievement, and student attitudes towards mathematics learning.

#### 3. Concentration of STEM and CBL Approaches

STEM or STEAM research is concentrated mainly in Indonesia and Turkey, with additional contributions from Spain, Cyprus, and Jordan or Palestine. Research focus in these countries generally relates to strengthening digital literacy, technology integration, and the development of 21st-century skills. Meanwhile, Culture-Based Learning shows a distinct concentration pattern in countries with strong local cultural heritage, such as Indonesia, Malaysia, and Zimbabwe. In this context, mathematics is positioned as part of everyday cultural practices, making learning more meaningful and contextual for students

Distribution by Education Level

Table 1. Distribution study by education level

Education Level	PjBL (17)	STEM (10)	CBL (7)	Total
Elementary School (Primary Education)	6	3	2	11
Junior High School (Junior High/Middle School)	7	3	2	13
Senior High/Vocational School (Senior High/Vocational)	4	4	3	10
<b>Total</b>	<b>17</b>	<b>10</b>	<b>7</b>	<b>34</b>

An analysis of the research subjects indicates that the implementation of PjBL, STEM, and CBL encompasses all levels of primary and secondary education. The distribution of studies is relatively balanced across the elementary, middle, and high school levels, demonstrating that these innovative learning models are not restricted to specific educational stages within the K-12 context.

At the elementary school level, there are eleven studies. PjBL dominates with six studies, accompanied by STEM with three studies and CBL with two studies. Research at this level generally focuses on fostering positive attitudes toward mathematics and developing fundamental problem-solving skills. At the junior high school level, there are thirteen studies. PjBL also serves as the primary approach with seven studies, followed by STEM and CBL with three studies each. The focus here often involves more abstract materials, such as algebra, geometry, and probability, to help students visualize complex concepts.

At the senior high and vocational school level, there are ten studies. PjBL and STEM are equally prominent with four studies each, while CBL accounts for two studies. Research at this stage is generally directed toward strengthening students' academic and vocational readiness, including the utilization of advanced learning technologies and the enhancement of competencies to prepare for the transition to higher education or the workforce.

Quantitative Meta-Analysis

Quantitative analysis was conducted on 34 empirical studies that met the inclusion criteria to estimate the effect size of implementing Project-Based Learning (PjBL), STEM, and Culture-Based Learning (CBL) on mathematics learning outcomes. Considering variations in study populations and designs, this analysis used a Random Effects Model with Cohen's d index.

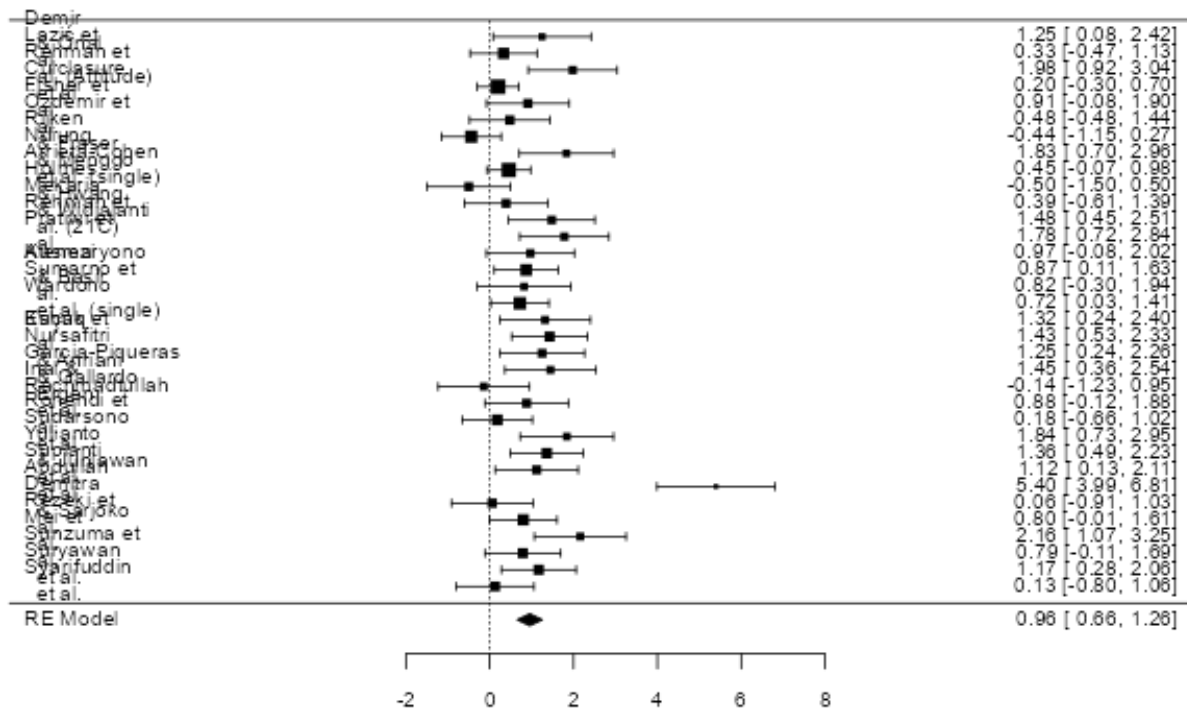


Figure. 2 Forest Plot

Based on the synthesis of data from 34 studies, effect sizes varied from the lowest value of  $d = -0.50$  to the highest of  $d = 5.40$ . The pooled analysis results showed that the implementation of innovative learning models (PjBL, STEM, and CBL) collectively had a significant positive impact on mathematics learning outcomes. The average pooled effect size was  $d = 0.99$  (95% CI: 0.655, 1.256) (Total N studies = 34). According to Cohen's criteria, this value is categorized as a Large Effect. This indicates that, on average, students learning with PjBL, STEM, or CBL approaches show improved mathematics performance. A visual representation of the individual study effect sizes, subgroup estimates, and the overall pooled estimate along with their respective 95% confidence intervals is presented in the Forest Plot (Figure 2)

### Subgroup Analysis

To answer the research objective regarding comparative effectiveness, subgroup analysis was conducted. A summary of statistics for each approach is presented in Table 2.

**Table 2.** Comparison of Average Effect Sizes of PjBL, STEM, and CBL

Instructional Approach	Number of Studies (k)	Mean Effect Size (d)	Effect Size Range (Min–Max)	Effect Category
Project-Based Learning (PjBL)	17	0.74	-0.50 to 1.98	Moderate–Large
STEM/STEAM	10	1.07	-0.14 to 1.84	Large
Culture-Based Learning (CBL)	7	1.50	0.06 to 5.40	Very Large

Project-Based Learning (PjBL), represented by the largest number of studies ( $k = 17$ ), yielded a mean effect size of  $d = 0.74$ , corresponding to a moderate to large effect. However, the effect size distribution was highly dispersed, ranging from negative ( $d = -0.50$ ) to very large positive effects ( $d = 1.98$ ). This variability indicates that the effectiveness of PjBL is highly contingent upon implementation factors, such as instructional design quality, teacher expertise, and contextual conditions.

STEM/STEAM ( $k = 10$ ) demonstrated a higher and more consistent mean effect size of  $d = 1.07$ , categorized as a large effect. The range of effect sizes ( $-0.14$  to  $1.84$ ) suggests relatively stable effectiveness across studies. This consistency indicates that interdisciplinary integration and the use of technology in STEM-based instruction provide robust support for improving mathematical performance.

Culture-Based Learning (CBL) ( $k = 7$ ) produced the highest mean effect size at  $d = 1.50$ , classified as a very large effect. However, this group also exhibited the greatest variability, with effect sizes ranging from  $d = 0.06$  to  $d = 5.40$ . While the high average suggests strong potential for culturally contextualized learning to enhance mathematics achievement, the limited number of studies and extreme dispersion warrant cautious interpretation.

### Heterogeneity Analysis

Data analysis showed a very high level of heterogeneity among the studies involved. This was statistically confirmed by Cochran's Q-statistic ( $Q = 108.452$ ,  $p < 0.001$ ) and the  $I^2$  index ( $I^2 = 72.92\%$ ). This high heterogeneity validates the decision to use the Random Effects Model in this meta-analysis. The variation in results proves that differences in effect size are not merely due to sampling error but are caused by differences in essential characteristics among studies, such as the diversity of education levels tested (from elementary to high school), variations in geographical conditions, and the duration and intensity of each intervention.

### Publication Bias

Evaluation of potential publication bias was conducted using visual inspection of the Funnel Plot and the statistical Egger's Regression Test. Based on the Funnel Plot in Figure 3, the distribution of effect sizes shows a wide spread and is not entirely symmetrical. Most study plots are scattered outside the 95% confidence interval boundaries (diagonal lines). This distribution pattern confirms the high level of heterogeneity among studies ( $I^2 > 90\%$ ), indicating that result variability is strongly influenced by specific characteristics of each study (such as the type of approach: PjBL, STEM, or CBL), not merely sampling error.

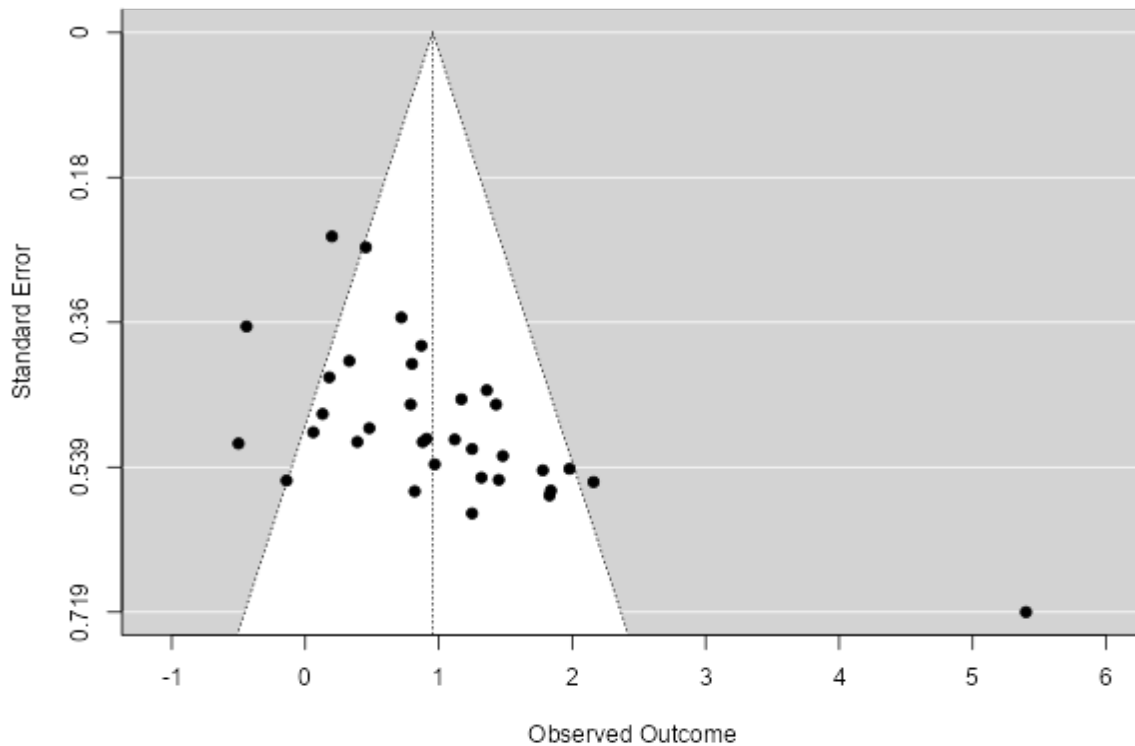


Figure. 3 Funnel Plot distribusi ukuran efek terhadap standar error

Although the plot visually appears asymmetrical with a tendency to cluster on the right side (positive effects), the presence of several plot points on the left side of the 0 axis (such as effect size -0.50) indicates that studies with negative results are included in this meta-analysis. This minimizes concerns about an absolute file-drawer problem. To statistically test the significance of this visual asymmetry, Egger's Regression Test was performed. A summary of the test results is presented in Table 3.

Table 3. Egger's Regression Test Results

Parameter	Coefficient (B)	t-value	p-value
Intercept (Constant)	4.149	4.254	0.000
Precision	-0.057	-0.328	0.745

Based on Table 3, the obtained intercept (Constant) value is 4.149 with a t-value of 4.254 and a significance level of  $p < 0.001$  (Sig. = 0.000). Because the p-value is  $< 0.05$ , the results of this regression test statistically confirm the presence of asymmetry in the data distribution. In meta-analysis studies, such asymmetry generally indicates potential publication bias. However, in the context of this study, these results must be interpreted considering the high level of heterogeneity among studies. The detected asymmetry likely reflects small-study effects, where studies with relatively small sample sizes (such as in some specific CBL interventions) report very extreme effect sizes, thus skewing the curve to one side. Given that this analysis has included studies with negative effect findings and used the Random Effects Model to accommodate this variance, the estimated pooled effect size is considered robust and valid for explaining the phenomenon of effectiveness of learning approaches overall.

## DISCUSSION

### Overall Effect of Innovative Pedagogies on Mathematics Achievement

The results of the meta-analysis of 34 studies show that the implementation of innovative learning approaches has a strong positive influence on mathematics learning outcomes, with an average effect size of  $d = 0.99$ , which falls into the high effect category. This finding indicates that student-centered learning approaches oriented towards authentic learning experiences have a significant impact on improving student mathematics performance.

This finding aligns with the constructivist perspective, which states that effective learning occurs when students actively construct knowledge through experience and interaction with the learning environment (Malik & Behera, 2024; Waite-Stupiansky, 2022). Approaches such as Project-Based Learning, STEM, and Culture-Based Learning provide opportunities for students to engage in contextual problem-solving activities, allowing for integration between conceptual understanding and practical application. Through this process, students not only master mathematical procedures but also develop higher-order thinking skills necessary for deep conceptual understanding. Additionally, innovative learning approaches encourage the development of 21st-century skills such as critical thinking, creativity, collaboration, and communication (Herlinawati et al., 2024; Martínez-Bravo et al., 2022). These skills play an important role in modern mathematics learning, which requires students not only to solve problems but also to analyze complex issues and apply mathematical concepts in real-world situations.

### **Comparative Effectiveness of PjBL, STEM, and Culture-Based Learning**

Subgroup analysis shows variation in effectiveness among the three analyzed approaches. Culture-Based Learning shows the highest average effect size ( $d = 1.50$ ), followed by STEM ( $d = 1.07$ ), and then Project-Based Learning ( $d = 0.74$ ). This difference indicates that each approach has distinct pedagogical mechanisms influencing the mathematics learning process.

Project-Based Learning is the most researched approach in this meta-analysis, with a total of 17 studies. The average effect size obtained is  $d = 0.74$ , which falls into the medium to high effect category. The effectiveness of PjBL can be explained through its main characteristics, which emphasize project-based learning and authentic problem-solving. In this approach, students engage in in-depth investigation of a problem, allowing them to build conceptual understanding through direct experience (Boardman et al., 2024; Lavado-Anguera et al., 2024; Thomas, 2000; Yusri et al., 2024). The project-based learning process also encourages active student engagement in discussion, collaboration, and reflection, which contributes to improved understanding of mathematical concepts (Rehman et al., 2023).

However, this meta-analysis shows that the effect size in the PjBL group has a very wide range. This variability is highlighted by an extreme outlier Arrieta-Cohen et al. (2024) which reported an exceptionally high effect size of  $d = 4.54$ . Such an extraordinary value is highly atypical and likely reflects specific contextual anomalies, such as severe baseline educational deficits during post-pandemic recovery in rural contexts, rather than a standard intervention effect. Excluding this outlier provides a more stable estimate of PjBL's effectiveness. As Batysheva & Kitibayeva, (2022) and Dewi (2022) explained, factors such as project design, teacher readiness, intervention duration, and availability of learning resources can significantly influence the success of this approach.

The STEM or STEAM approach shows an average effect size of  $d = 1.07$ , which falls into the high effect category. This result indicates that cross-disciplinary integration between science, technology, engineering, and mathematics significantly contributes to improved mathematics learning outcomes. The STEM approach allows students to understand mathematical concepts in the context of real-world applications through the integration of various disciplines (Bybee, 2013; Okwara & Pretorius, 2023). This integration helps students see the connections between mathematical concepts and scientific and technological phenomena, thereby increasing the relevance of learning. Furthermore, the use of digital technology in STEM learning also plays a role in facilitating the visualization of abstract mathematical concepts and enhancing the interactivity of learning (Sofroniou et al., 2025). This finding also reflects the development trend in STEM research, which increasingly integrates digital technology, such as the use of digital learning spaces and the Meta-STEM concept emerging in several recent studies. This technology integration provides opportunities for students to explore mathematical concepts through simulations and more dynamic learning environments.

Culture-Based Learning shows the highest average effect size,  $d = 1.50$ , which falls into the very high effect category. This finding indicates that learning that integrates students' cultural contexts has significant potential to improve understanding of mathematical concepts. Culture-based approaches make mathematical concepts more relevant to students' daily experiences. When mathematics is linked to local cultural practices, students more easily understand abstract concepts because they can connect them to familiar experiences (D'Ambrosio, 1985; Komalasari et al., 2018; Smith et al., 2022). Besides improving conceptual understanding, this approach can also increase learning motivation and student engagement in the learning process (Pagán, 2022; Rigney et al., 2020).

However, the interpretation of CBL's apparent superiority must be approached with extreme caution and critical methodological scrutiny. The CBL subgroup's mean is heavily distorted by one extreme outlier Abdullah et al. (2025) reporting an unprecedented effect size of  $d = 5.40$ . An effect magnitude of 5.40 represents an impossibility in typical educational interventions and is almost certainly a methodological artifact. This inflation could result from

measurement errors, ceiling effects in the assessment instruments, or severe anomalies in the study's control group design. As demonstrated in the sensitivity analysis, excluding this single study substantially reduces the CBL pooled estimate to a more realistic level.

Furthermore, the comparative advantage of both the CBL and STEM subgroups over PjBL is largely confounded by the inclusion of hybrid studies. Several studies categorized under CBL (e.g., integrating ethnomathematics) and STEM were fundamentally structured upon a Project-Based Learning framework. Consequently, the high effect sizes observed in the CBL and STEM groups may not reflect the efficacy of pure, isolated cultural or technological interventions. Instead, they likely represent the synergistic advantage of embedding rich contextual (cultural) or interdisciplinary (STEM) content into the robust, active-learning mechanics of PjBL.

### **Sources of Heterogeneity Across Studies**

This meta-analysis shows a very high level of heterogeneity among the analyzed studies. This variation is reflected in the wide range of effect sizes and the distribution of data in the funnel plot, which is not entirely symmetrical. High heterogeneity indicates that the effectiveness of learning approaches is not only determined by the learning model used but is also influenced by various contextual factors. Factors potentially affecting result variation include differences in education levels, geographical research contexts, research designs, and the duration and intensity of learning interventions. Additionally, the Egger test results indicate asymmetry that may be related to small-study effects, a condition where some studies with small sample sizes report very large effect sizes. [Sterne & Harbord \(2004\)](#) suggest that this phenomenon is relatively common in studies characterized by diverse implementation contexts and heterogeneous research designs, particularly in educational research. [Rücker et al. \(2011\)](#) further argue that asymmetry in a funnel plot should not necessarily be interpreted as definitive evidence of publication bias, as it may also arise from alternative sources, such as differences in participant characteristics between small- and large-scale studies, potential statistical artifacts in effect size estimation, or random variation.

### **Toward an Integrated Pedagogical Framework**

The findings of this meta-analysis also show a tendency towards integration among learning approaches. Several studies combine Culture-Based Learning with Project-Based Learning through the integration of project-based ethnomathematics. This combination shows that each approach has pedagogical strengths that complement each other. Project-Based Learning provides a structured project-based learning framework, STEM offers cross-disciplinary and technological integration, while Culture-Based Learning strengthens learning relevance through students' cultural contexts. Therefore, developing a learning model that integrates these three approaches has the potential to produce a more comprehensive pedagogical framework for improving the quality of mathematics learning.

### **Educational Implications**

The findings of this study have concrete implications for mathematics education practice and policy. Teachers need to consider implementing more contextual and activity-based learning approaches to improve students' understanding of mathematical concepts. However, to avoid superficial implementation, teachers should not merely insert cultural symbols or technological tools into traditional lectures. Instead, they should utilize PjBL as the structural engine. For instance, educators can design mathematical projects where students calculate geometric transformations by analyzing local architectural designs or traditional dances (a hybrid of PjBL and CBL), or model environmental data using digital applications (a hybrid of PjBL and STEM).

### **Limitations of the Study**

This study has several limitations that should be considered when interpreting the results. First, the number of studies using the Culture-Based Learning approach is still relatively limited, so generalization of findings needs to be done cautiously. Second, the level of heterogeneity among studies is very high, indicating variation in the contexts of learning implementation. Third, the geographical distribution of research is still dominated by certain countries, especially Indonesia, so the global representation of research is not yet fully balanced.

## **CONCLUSION**

This meta-analysis demonstrates that the implementation of student-centered learning models, namely Project-Based Learning (PjBL), STEM/STEAM, and Culture-Based Learning (CBL), collectively has a significant positive impact on mathematics learning outcomes with a high effect category. Subgroup analysis shows variation in effectiveness, with CBL yielding the highest nominal effect size, followed by STEM/STEAM and PjBL. However, these comparative findings must be interpreted with significant caution. The high level of heterogeneity across the dataset, the small number of studies in the CBL subgroup, and the confounding presence of hybrid interventions and extreme outliers

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indicate that these effect sizes are heavily influenced by specific implementation contexts rather than the isolated efficacy of the approaches themselves.

Despite these variables, the findings confirm that each approach possesses complementary pedagogical strengths. Integrating the structured framework of PjBL with the interdisciplinary elements of STEM and the contextual relevance of CBL holds strong potential as a conceptual basis for developing hybrid mathematics instruction. To appropriately qualify the practical recommendations offered to educators and policymakers, several methodological limitations of this study must be acknowledged. First, the geographical distribution of the literature is highly concentrated, limiting the global generalizability of the findings. Second, the categorization of hybrid instructional designs introduces ambiguity, making it challenging to isolate the pure effects of each distinct approach. Finally, the exceptionally wide confidence intervals and outlier-driven variance in the CBL subgroup restrict the certainty of its comparative superiority.

To address these gaps, future research should focus on three specific directions. First, there is a critical need for adequately powered, randomized controlled trials that evaluate pure, non-hybrid implementations of Culture-Based Learning in mathematics to establish more reliable baseline estimates. Second, future meta-analyses should conduct subgroup analyses by specific mathematics topic domains (e.g., algebra, geometry, or statistics) to determine whether certain pedagogies are uniquely suited to particular cognitive demands. Finally, longitudinal follow-up studies are essential to assess whether the immediate gains observed from PjBL, STEM, and CBL translate into long-term retention of mathematical competencies and 21st-century skills.

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# Effects of Project-Based Learning, STEM Education, and Culture-Based Learning on K-12 Mathematics...

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## Appendix

No.	Study (Author & Year)	Country	Education Level	Intervention / Approach	Mathematics Topic	Sample Size (N)	Effect Size (d)
1	Demir & Önal (2021)	Turkey	Junior High School	PjBL	Data Processing	35	1.25
2	Lazić et al. (2021)	Serbia	Elementary School	PjBL	Measurement	147	0.33
3	Rehman et al. (2023)	Pakistan	Elementary/Junior High School	PjBL	Attitude toward Mathematics	70	1.98
4	Culclasure et al. (2023)	United States	Senior High School	PjBL (NTN Model)	End of Course Math	1078	0.20
5	Fisher et al. (2021)	Indonesia	Junior High School	PjBL	Problem Solving	65	0.91
6	Özdemir et al. (2015)	Turkey	Junior High School	PjBL	Ratio, Proportion, and Percentage	70	0.48
7	Rijken & Fraser (2024)	Australia	Junior/Senior High School	PjBL	Academic Achievement	284	-0.44
8	Ndiung & Menggo (2024)	Indonesia	Elementary School	PjBL	Creative Thinking & Problem Solving	43	1.83
9	Arrieta-Cohen et al. (2024)	Colombia	Elementary School	PjBL	Basic Mathematics	201	4.54
10	Holmes & Hwang (2016)	United States	Senior High School	PjBL	Algebra & Geometry	60	-0.50
11	Mekaria & Widjajanti, (2018)	Indonesia	Junior High School	PjBL	Reasoning & Achievement	60	0.39
12	Rehman et al. (2023)	Pakistan	Elementary School	PjBL	21st Century Skills	70	1.48
13	Pratiwi et al. (2020)	Indonesia	Junior High School	PjBL + Learning Styles	Mathematical Communication	64	1.78
14	Alenezi (2023)	Saudi Arabia	Senior High School	PjBL + Madrasati Platform	Learning Achievement	50	0.97
15	Kusmaryono & Basir (2024)	Indonesia	Junior High School	PjBL + YouTube Media	Learning Achievement	180	0.87
16	Sumarmo et al. (2024)	Indonesia	Elementary School	PjBL + Bilingual Materials	Literacy and Numeracy	39	0.82
17	Wardono et al. (2020)	Indonesia	Junior High School	PjBL + RME + Schoology	Mathematical Literacy	64	0.72
18	Eshaq (2024)	Saudi Arabia	Junior High School	STEM	Mathematics Learning Achievement	50	1.32
19	Küçük et al. (2023)	Turkey / Northern Cyprus	Elementary School	SP-STEAM	Mathematics Achievement & Critical Thinking	104	1.43
20	Nursafitri & Anriani, (2023)	Indonesia	Junior High School	STEM	Conceptual Understanding	64	1.25
21	Garcia-Piqueras & Ruiz-Gallardo (2021)	Spain	Senior High School	PjBL + Green STEM	Mathematical Proficiency	46	1.45
22	İnal & Ergen (2025)	Turkey	Elementary School	STEM + 5E Model	Problem-Solving Ability	42	-0.14
23	Rachmadtullah et al. (2023)	Indonesia	Elementary School	STEM + Metaverse	Critical Thinking	62	0.88
24	Rohendi et al. (2023)	Indonesia	Vocational High School	STEM + Online Media	Mathematical Ability	120	0.18
25	Sudarsono et al. (2022)	Indonesia	Senior High School	STEM + Local Culture	Problem Solving	50	1.84
26	Yulianto & Juniawan (2025)	Indonesia	Junior High School	STEM + Digital Learning Space	Mathematical Creativity	120	1.36
27	Supianti et al. (2025)	Indonesia	Junior/Senior High School	PjBL + STEAM	Mathematical Literacy	68	1.12
28	Abdullah et al. (2025)	Malaysia	Junior High School	Ethnomathematics	Isometric Transformation	60	5.4
29	Demitra & Sarjoko (2018)	Indonesia	Senior High School	CBL (Handep)	Rational Exponents	66	0.06
30	Rezeki et al. (2025)	Indonesia	Junior High School	Culture-Based Learning	Mathematics Learning Outcomes	141	0.8
31	Mei et al. (2025)	Indonesia / Malaysia	Elementary School	Problem-Solving + Ethnomathematics	Creative Thinking	75	2.16
32	Sunzuma et al. (2021)	Zimbabwe	Senior High School	Ethnomathematics	Consumer Arithmetic	90	0.79
33	Suryawan et al. (2023)	Indonesia	Junior High School	PBL + Ethnomathematics + Multimodal	Critical Thinking	100	1.17
34	Syarifuddin et al. (2025)	Indonesia	Elementary School	PjBL + Ethnomathematics + GeoGebra	Mathematical Creativity	80	0.13