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The effectiveness of problem-based learning in enhancing mathematical literacy: A systematic meta-analysis

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Abstract

This meta-analysis aims to evaluate the effectiveness of Problem-Based Learning (PBL) in improving students' mathematical literacy by reviewing empirical studies comparing PBL with conventional learning. The results show that PBL significantly improves mathematical literacy, with an effect size of 1.165, categorized as high. However, the effectiveness of PBL is influenced by moderating factors such as education level, student learning style, learning duration, and problem relevance. Findings suggest that PBL is more effective at the junior high school level than senior high school, although the difference is not statistically significant ($p > 0.05$). This study is limited by the short intervention duration in most analyzed studies and the lack of investigation into external factors like student motivation and teacher roles. Future research is recommended to conduct longitudinal studies, explore the integration of digital tools, and compare the use of real-world and academic problems in PBL. Overall, the findings confirm that PBL is an effective and promising approach for enhancing mathematical literacy when implemented with attention to relevant contextual and learner-specific factors.

Keywords: effect size; mathematical literacy; meta-analysis; problem-based learning

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Introduction

In the digital era and the Industrial Revolution 4.0, mathematical literacy has become crucial for achieving academic success and making informed decisions based on data in various aspects of life (OCDE, 2023). It involves more than just basic arithmetic and includes the ability to interpret, analyze, and solve problems in real-life contexts using appropriate mathematical concepts. The Program for International Student Assessment has been widely used to measure students' levels of mathematical literacy across different countries. Over the past two decades, its results have shown significant gaps in achievement, particularly in developing countries that still struggle with implementing effective learning strategies (Kang & Cogan, 2020).

Problem-Based Learning has been introduced as a promising teaching approach to enhance mathematical literacy. This model emphasizes solving real-world problems as the core of the learning process, aiming to develop students' understanding of concepts, critical thinking, and problem-solving skills (Ahdhianto et al., 2020). It supports deeper mathematical understanding through active investigation, collaboration, and reflection during the learning experience (Hung, 2013). However, studies examining the impact of Problem-Based Learning on mathematical literacy have produced mixed results. While some have shown significant improvements compared to traditional teaching methods Wardono et al. (2018), others have found more limited or insignificant outcomes (Husna & Kurniasih, 2023).

A systematic and meta-analytical review is urgently needed to summarize and evaluate existing empirical evidence on the effectiveness of Problem-Based Learning (PBL) in enhancing mathematical literacy. This review offers a more comprehensive quantitative estimation of PBL's impact while identifying moderating factors such as education level, research design, and assessment methods (Anwar & Budi Waluya, 2018; Malinowski, 2023; Muzana et al., 2021).

Although PBL is widely recognized as an effective approach to supporting mathematical understanding, studies have reported inconsistent findings regarding its influence on mathematical literacy. While some research highlights significant improvements due to PBL, others suggest its effects vary depending on the learners' education level, research methodology, and implementation strategies (Maslihah et al., 2021; Rojas & Benakli, 2020). Moreover, most existing studies rely on quantitative or quasi-experimental designs and lack integrated analysis across different contexts. Limitations in sample size, geographical scope, and varied literacy assessment tools hinder strong generalizations (Voithofer, 2012). Despite the emphasis on problem-solving benefits, few studies assess PBL's large-scale impact on mathematical literacy (Nazmihaolah et al., 2025).

To overcome this limitation, a meta-analysis is needed to synthesize the results of various studies systematically and quantitatively. By using a meta-analytic approach, this study will provide more accurate and generalizable effect estimates and identify moderating factors that may affect the effectiveness of PBL on mathematical literacy, such as education level, sample characteristics, and research design. Thus, this study will bridge the existing research gap and provide practical implications for developing evidence-based education policies.

In line with the urgency of improving mathematical literacy in the global education system, this study aims to conduct a meta-analysis-based systematic synthesis of empirical studies that have examined the effectiveness of Problem-Based Learning (PBL) in developing students' mathematical literacy. By integrating the findings from various published studies, this study seeks to provide a more accurate and general quantitative estimate of the impact of PBL on mathematical literacy at various levels of education. Based on these objectives, this article seeks to answer the question of to what extent is Problem-Based Learning (PBL) effective in improving mathematical literacy compared to conventional learning methods. Moreover, do moderating factors such as education level and subject vary the strength of the effect of intervention using the PBL model in improving students' mathematical literacy so that these factors lead to heterogeneous students' mathematical literacy?

This study aims to contribute both theoretically and practically to the field of mathematics education. Theoretically, it will reinforce or challenge existing findings on the effectiveness of Problem-Based Learning (PBL) through an evidence-based approach, supporting the development of research on mathematical literacy and PBL implementation. The findings can be a reference for educators, curriculum developers, and policymakers in designing data-driven instructional strategies to enhance students' mathematical literacy.

This study is expected to significantly contribute to mathematics education literature by adopting a systematic and comprehensive meta-analytic approach to evaluate the effectiveness of Problem-Based Learning (PBL) in enhancing students' mathematical literacy. Unlike previous studies, which are generally experimental and focused on specific contexts, several scholarly sources have recommended cross-study evidence synthesis to achieve a more holistic understanding and statistically generalizable results (Nazmihaolah et al., 2025). In response to this need, the present research integrates empirical findings through a data-driven meta-analytic method, strengthening theoretical and practical foundations for implementing PBL across various educational levels.

In the methodological aspect, this study applies the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework to ensure transparency in article selection and analysis. In addition, meta-analysis will use random or fixed-effects models to obtain more robust and reliable effect estimates (Halme et al., 2023). With this approach, this study not only presents a summary of results from various studies but also evaluates the heterogeneity of PBL effects on mathematical literacy that has not been widely studied in previous studies (Nazmihaolah et al., 2025).

Furthermore, this study identified moderator factors that may influence the effectiveness of PBL in improving mathematical literacy, such as the level of education. Thus, this study confirmed the effectiveness of PBL in general and provided insights into the conditions and variables that contribute to the successful implementation of PBL in improving mathematical literacy.

Methods

This study used a meta-analysis approach to synthesize the results of empirical research on the effectiveness of Problem-Based Learning (PBL) in improving mathematical literacy. Meta-analysis was chosen because it can provide a quantitative synthesis of various research results conducted previously, thus enabling a more generalizable estimation of the impact of PBL compared to individual studies (Morris, 2023). To ensure transparency and replicability, the meta-analysis process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Panda, 2024).

Data collection was conducted through two primary sources, namely Scopus and Google Scholar, to obtain research published in internationally reputable journals and additional relevant studies. Articles were searched using a combination of keywords such as "Problem-Based Learning" OR "PBL," "Mathematical Literacy" OR "Numeracy," and "Experiment" OR "Quasi-Experiment" OR "Control Group." To increase the scope of research obtained, the search was also conducted manually by cross-referencing relevant articles.

This research applied strict inclusion and exclusion criteria to ensure that only high-credibility studies were analyzed. The included studies had to meet the following requirements: (1) published within the last 10 years (2014–2024) to ensure relevance to recent research developments; (2) available in journals indexed by Scopus or Google Scholar with full access to the necessary data; (3) employed an experimental or quasi-experimental research design with a control group for comparison; (4) reported effect size data convertible for meta-analyses, such as means, standard deviations, effect sizes, or p-values; and (5) explicitly investigated the impact of PBL on mathematical literacy.

In the initial stage, 125 articles were identified through database searches. After a rigorous screening process based on the inclusion and exclusion criteria, only 20 articles met the requirements and were included in the meta-analysis. The article selection process is detailed in Figure 1. Conversely, conceptual studies, those lacking control groups, or studies that did not provide sufficient data for effect size calculation were excluded from the analysis.

Data analysis in this study was conducted using JASP (Jeffreys's Amazing Statistics Program), a user-friendly open-source statistical software that supports meta-analysis procedures. JASP enables the calculation of effect sizes, confidence intervals, and heterogeneity tests and provides visualizations such as forest and funnel plots. The software supports both frequentist and Bayesian approaches transparently and efficiently (Wagenmakers et al., 2018).

Results

Research publication series

A search through Google Scholar and Scopus yielded 125 publications classified by author, title, keywords, abstract, and source title. In addition, to control the results of the study, we used selected reporting items for the protocol technique of systematic review and meta-analysis

(PRISMA). The steps of PRISMA can be clearly seen at **Error! Reference source not found.** . Meanwhile, this study used Scopus and google scholar databases.

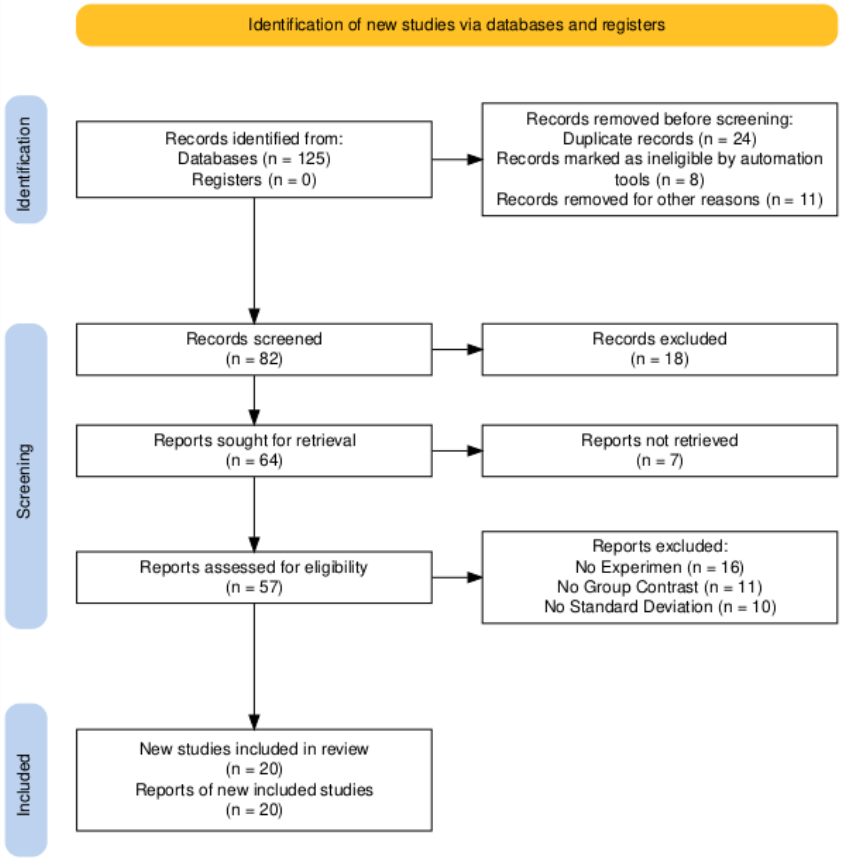

Figure 1. Prism flow diagram

Based on the PRISMA diagram results, 125 articles were initially identified from academic databases related to PBL and mathematical literacy. Before screening, 43 articles were excluded due to duplication (24), automation filtering (8), and limited access or metadata issues (11). The remaining 82 articles underwent further evaluation, with 18 removed for irrelevance to the topic. Of the 64 articles requested in full text, 7 could not be accessed. At the eligibility stage, 57 articles were assessed, and 37 were excluded for reasons including non-experimental design (16), absence of control groups (11), or missing standard deviation data (10). Ultimately, 20 articles met all inclusion criteria and were included in the meta-analysis. This thorough process ensured only high-quality studies with relevant, empirical contributions were analyzed. Notably, only 16% of the initially identified articles qualified, reflecting the strict methodological and data clarity standards, as well as access limitations to some potentially relevant sources.

Data coding and analysis

The data coding on the coding sheet contains some information such as author, and moderating factors. Several moderating factors involved in this study were investigated and examined to ascertain their role in students' mathematical literacy, as outlined inTable 1.

Table 1. Document distribution by level

No.	Author Name	Level
1	(Farhan et al., 2021)	Elementary School
2	(Zhang, 2024	Senior High School
3	(Awami et al., 2022)	Senior High School
4	(Husna & Kurniasih, 2023)	Senior High School
5	(Khurin'in et al., 2024)	Senior High School
6	(Al-Fitriani et al., 2023)	Senior High School
7	(Kusumawati et al., 2024)	Junior High School
8	(Rismayanti & Wahyuni, 2022)	Junior High School
9	(Zain & Masamah, 2023)	Junior High School
10	(Mutiasari et al., 2024)	Junior High School
11	(Pamungkas & Franita, 2019)	Junior High School
12	(Prihatiningtyas & Buyung, 2023)	Junior High School
13	(Tabun et al., 2020)	Junior High School
14	(Astuti, 2020)	Junior High School
15	(Kurnila et al., 2022)	Junior High School
16	(Ananda & Fauziah, 2022)	Junior High School
17	(Ornawati et al., 2023)	Junior High School
18	(Fery et al., 2017)	Junior High School
19	(Ambarwati & Kurniasih, 2021)	Junior High School
20	(Andini & Siregar, 2024)	Junior High School

Table 1 shows that among the 20 studies analyzed, most focused on junior high school students (15 studies or 75%), followed by high school (4 studies or 20%), and only one at the elementary level (5%). This indicates a research focus on junior high school, likely due to students' cognitive transition from concrete to abstract thinking at that stage. The limited studies at the elementary and high school levels suggest a research gap worth exploring further. To estimate the impact of PBL on mathematical literacy, this meta-analysis used Hedge's g, which adjusts for small sample sizes and corrects bias from unequal group sizes, providing a more accurate effect size estimate (Borenstein et al., 2009):

$$g = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}}} \times \left(1 - \frac{3}{4df - 1}\right)$$

Cohen-Shikora et al. (2018) classified the results into four categories. Starting from weak to strong, g = 0.00 - 0.20 is considered weak, g = 0.21 - 0.50 moderate, g = 0.51- 1.00 strong, and finally g > 1.00 is measured as very strong. Furthermore, another Z-test was also used to test the significance of the intervention using the PBL Model on students' mathematical literacy (Rothstein et al., 2006). In addition, to test the significance of moderating factors in causing students' heterogeneous mathematical literacy, Cochran's Q test was used (Higgins et al., 2003).

Furthermore, the statistical data in the meta-analysis is said to be publication bias (Cooper et al., 2017). Consequently, to ensure that the statistical data avoided publication bias, funnel plot analysis and Egger regression test were conducted (Rothstein et al., 2006). This interpreted that the statistical data collected did not exhibit significant publication bias.

Data analysis

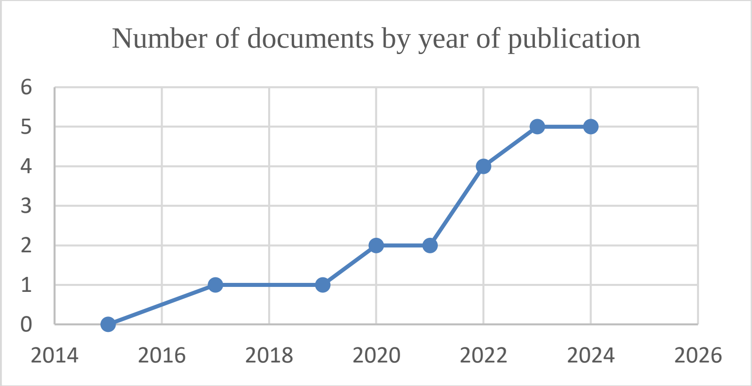

Figure 1. Document distribution by year

The graph illustrates a growing trend in publications from 2015 to 2024. While there were no studies published in 2015, a gradual increase began from 2016 to 2019 with only one or two documents annually. A more noticeable rise occurred in 2020 and 2021, followed by a significant spike starting in 2022, continuing through 2023 and 2024 with five publications each year. This surge suggests growing academic interest, possibly influenced by curriculum shifts, technological advances, or increased research funding. With the upward trend expected to persist, further analysis is needed to understand the drivers behind this growth. To complement this trend analysis, the Pooled Effect Size Test results are presented in Table 2.

Table 2. *Pooled Effect Size Test*

Estimate	Standard Error	z	t	p
1.165	0.205	5.691	5,691	< .001

The results of the meta-analysis shown in Table 2 Pooled Effect Size Test indicate that Problem-Based Learning (PBL) has a significant effect on mathematical literacy. The effect size value of 1.165 indicates a large effect based on the standard interpretation of Cohen's d, which means that the implementation of PBL substantially improves mathematical literacy compared to conventional learning methods. In addition, the relatively small standard error value (SE = 0.205) indicates that the effect size estimate is quite stable, with low variability among the studies analyzed.

Furthermore, the high values of $z = 5.691$ and $t = 5.691$ indicate that these results have strong statistical significance, where the p value < 0.001 confirms that the results of this meta-analysis did not occur by chance, but rather reflect the real effect of PBL on mathematical literacy. With a very high level of significance, it can be concluded that PBL is an effective learning approach in improving students' mathematical literacy.

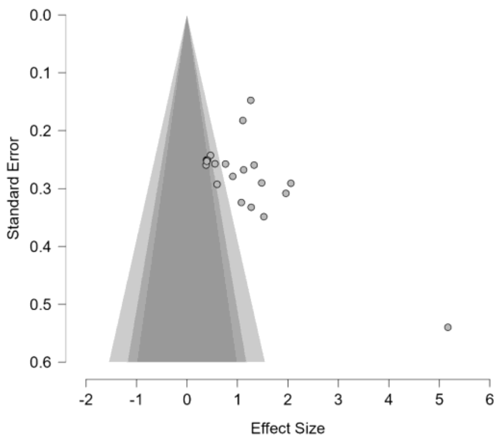

Figure 2. Funnel Plot

Table 3. Weighted regression test for funnel plot asymmetry

	Asymmetry Test			Limit Estimate		
Estimates	t	df	p	Estimate	Lower 95% CI	Upper 95% CI
20	1.611	18	0.125	0.126	-1.090	1.342

The funnel plot analysis results onFigure 2 show that the distribution of the effect size data set is symmetrical. This means that the effect size data from each document involved in this study is resistant to publication bias. To ensure that the distributed effect size data is symmetrical, the Egger regression test is conducted. The Egger regression test results show that the t-value is 1.611 and the p-value is 0.125. This provides strong evidence that the data is symmetric.

Figure 3 is a forest plot used in meta-analysis to display the results of individual studies in estimating a combined effect. This forest plot illustrates the relationship between certain variables measured in different studies using Fisher's z to r conversion. The horizontal axis shows the correlation value (r), while each study listed on the vertical axis presents its effect estimate along with its confidence interval (CI).

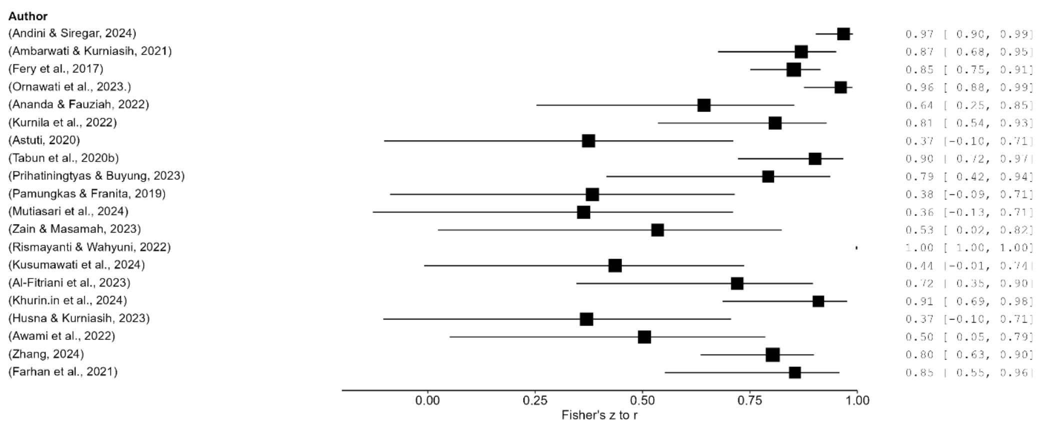

Figure 3 . Forest plot

From this forest plot, it can be observed that most studies show a positive effect, with correlation values ranging from 0.12 to 0.97. Some studies, such as Andini & Siregar (2024), Ornawati et al. (2023) and Khurin'in et al. (2024), had high correlations (above 0.80), with relatively narrow confidence intervals, indicating high precision in the effect estimation. In contrast, several other studies, such as Astuti (2020), Mutiasari et al. (2024) and Husna & Kurniasih (2023), have a wider range of intervals, which may indicate greater uncertainty in the results.

Overall, the results of this forest plot indicate that the effects assessed in this meta-analysis tend to be positive, although there is some variation between studies. Differences in effect size may be due to methodological factors, such as differences in sample population, measurement instruments, or research design. To ensure the accuracy of the results, further analysis of the heterogeneity between studies as well as exploration of moderator factors that may affect the relationship under study is needed.

Moderating factor analysis

Furthermore, to see the phenomenon by analyzing and identifying the causes of effect sizes that tend to be low or high, a systematic approach is needed by considering the methodological characteristics of each study included in the meta-analysis. One effective way is to compile a comparative analysis table that includes the main variables that can affect effect size differences. The following is an analysis table based on high and low trends.

Table 4. Moderating factors

Level	Effect Size	Results	Limitations
Junior High School	High	Ornawati et al. (2023) emphasized the importance of considering different learning styles (auditory, visual, kinesthetic) in the implementation of PBL, which can lead to tailored educational strategies that enhance student engagement and understanding. Andini & Siregar (2024) foster important skills such as teamwork, responsibility, and communication among students	Ornawati et al. (2023) rely mainly on quantitative methods, potentially missing qualitative insights that could enhance understanding of students' experiences with different learning styles. Andini & Siregar (2024) Andini & Siregar (2024) Don't consider external factors, such as students' prior knowledge or social background, and fail to explore various PBL strategies, limiting understanding of how different approaches affect students' mathematical literacy.
	Low	Astuti (2020) explains that in the Problem-Based Learning model, the teacher does not initially present the material but instead introduces a real-life problem related to the topic to be studied. Mutiasari et al. (2024) note	Astuti (2020) highlights the lack of qualitative data to understand students' experiences and perceptions of PBL, limiting deeper insights into its effectiveness. Mutiasari

Level	Effect Size	Results	Limitations
		that the large standard deviation in the control class (18.53) compared to the experimental class (14.86) suggests considerable variation in students' baseline abilities, which may weaken the impact of the PBL intervention.	et al. (2024) did not explore the integration of cultural contexts or compare PBL with alternative teaching methods beyond the conventional approach.
Senior High School	High	Khurin'in et al. (2024) Students in this study already have a good basic ability, as evidenced by the pretest data which shows 80.95% of students are in the medium and high categories. With a better ability background, students can more easily understand the problem-solving process in PBL.	Khurin'in et al. (2024) This study only compared experimental and control groups without analyzing factors that might moderate the effectiveness of PBL.
	Low	Husna & Kurniasih (2023) conducted the study over 6 meetings of 90 minutes each, which is insufficient for optimal PBL implementation. The limited time prevents students from fully developing their critical thinking and mathematical literacy. Additionally, the problems used were mostly academic, with little focus on real-life contextual problems.	Husna & Kurniasih (2023) note that LiveWorksheet emphasizes interactive exercises but does not fully support the exploration aspect of PBL. The absence of interactive simulations or visual modeling makes it difficult for students to deeply understand trigonometry concepts.

Analysis of moderating factors reveals that the effectiveness of Problem-Based Learning (PBL) on mathematical literacy is influenced by variables such as students' learning styles, prior knowledge, learning duration, and the contextual relevance of problems. When these are considered, PBL tends to yield more significant improvements (Huang & Chen, 2024; Rehman et al., 2023). At the junior high school level, Ornawati et al. (2023) emphasized the importance of aligning PBL with students' learning styles to enhance engagement, though their study lacked qualitative insights. Similarly, Andini & Siregar (2024) highlighted gains in teamwork and communication but did not examine prior knowledge or socio-cultural factors. Conversely, studies by Astuti (2020) and Mutiasari et al. (2024) reported limited effects, attributing this to varied initial abilities and lack of cultural context in PBL tasks. At the high school level, Khurin’in et al. (2024) found more positive outcomes due to students’ stronger foundational skills, though moderating variables were not analyzed. On the other hand, Husna & Kurniasih (2023) found limited success due to short implementation duration and lack of real-world problem contexts. To examine differences in PBL effectiveness across educational levels, the Cochrane Q test can be applied, as detailed in the table below.

Table 5. Heterogeneity analysis results

Level	Effect Size	criteria	P-Value
Junior High School	1,274	Very High	0,084
Senior High School	0,882	Medium	

Based on the results of the heterogeneity analysis presented in Table 5, it can be seen that the effect size value at the junior high school level is 1.274, which is categorized as very high, while at the high school level it is 0.882, which falls into the medium category. This difference indicates that the variables studied have a stronger influence at the junior high school level than at the senior high school level. However, to determine whether the variation in effect size is significant or not, the Cochrane Q Heterogeneity Test was conducted, with the P-Value parameter as an indicator of diversity between studies.

Cochrane's Q test was employed in this meta-analysis to examine whether the variation in effect sizes across studies is due to random sampling error alone or influenced by other systematic factors. This test is essential for assessing the homogeneity of the studies included in a meta-analysis, which determines the appropriateness of pooling their results (Borenstein et al., 2009).

Cochrane's Q is an inferential statistical test that evaluates the null hypothesis that all studies share a common effect size. A significant Q statistic (p-value < 0.05) indicates that there is more variability in the effect sizes than would be expected by chance alone, suggesting the presence of heterogeneity (Borenstein et al., 2009). In this study, although the effect size for junior high school students (1.274) was higher than that for senior high school students (0.882), the p-value of 0.084 from the Q test suggests that the difference is not statistically significant.

From the results of this analysis, it can be concluded that although there is a difference in effect size between junior and senior high school, the heterogeneity is not statistically significant. This suggests that the effectiveness of the intervention or variable under study tends to be stable and consistent across both levels. However, the difference in effect size indicates the presence of contextual factors such as learning methods, student characteristics, or curriculum differences that may affect the results of the study. Therefore, future research could focus more on analyzing moderators, such as the type of learning strategy or students' cognitive level, to identify factors that contribute to effect size variations.

Discussion

This meta-analysis confirms that Problem-Based Learning (PBL) significantly enhances students' mathematical literacy, with an effect size of 1.165 categorized as very high. This supports prior studies showing that PBL promotes active problem solving, deeper conceptual understanding, and improved critical and reflective thinking (Nugraha, 2021; Suparman et al., 2021). Contextual factors play a key role, as real-world problems yield higher effects than purely academic tasks. Adaptation to students' learning styles Ornawati et al. (2023) and accounting for prior abilities Mutiasari et al. (2024) also influence outcomes. While PBL proves effective, variation in impact highlights the importance of considering factors such as educational level, design, duration, and problem relevance (Astuti, 2020; Husna & Kurniasih, 2023; Khurin'in et al., 2024; Mutiasari et al., 2024; Ornawati et al., 2023).

The effectiveness of Problem-Based Learning (PBL) in enhancing mathematical literacy is significantly moderated by factors such as learning style, initial ability, learning duration, and problem type. Ornawati et al. (2023) found that visual learners benefit more from PBL due to their ease in interpreting diagrams, while auditory learners require richer verbal interaction, indicating that mismatched instructional strategies may reduce PBL's impact. Initial ability also plays a key role—students with stronger mathematical foundations adapt better to PBL than those with weaker backgrounds, highlighting the need for structured scaffolding (Mutiasari et al., 2024). Moreover, Husna & Kurniasih (2023) emphasized that short implementation periods (e.g., six sessions) limit students' opportunities for deep engagement, making sufficient duration essential for effective PBL.

The type of problems used in PBL plays a crucial role in its effectiveness. Khurin'in et al. (2024) found that real-world problems were more effective in improving mathematical literacy compared to academic problems, as students can relate math to their lives. In contrast, Mutiasari et al. (2024) showed that students struggled to apply concepts when given only academic problems without real-world context. Thus, selecting relevant, contextual problems is essential for successful PBL implementation.

This meta-analysis revealed that studies with higher effect sizes often featured mature PBL designs, adequate infrastructure, and longer learning durations. For example, Khurin'in et al. (2024) found significant gains in mathematical literacy when PBL was well-implemented, with real-world problems and strong student abilities. However, Husna & Kurniasih (2023) noted that shorter learning times and insufficiently contextualized problems reduced PBL effectiveness.

Teaching experience also influences PBL success. Andini & Siregar (2024) highlighted that experienced teachers can better guide students in problem-solving, enhancing learning outcomes. Conversely, studies with lower effect sizes showed that inadequate teacher training hindered students' understanding of complex problems.

Environmental factors, such as school resources and access to technology, also impact PBL effectiveness. Research in schools with better resources produced higher effect sizes, while studies with limited technology, such as Husna & Kurniasih (2023), showed suboptimal results. Therefore, the success of PBL depends not only on the method design but also on the learning environment and educational resources.

This meta-analysis confirms that the effectiveness of PBL in improving mathematical literacy depends on factors such as students' learning style, initial ability, learning duration, and problem relevance. The findings suggest that optimizing PBL design, environmental support, and problem selection can enhance its effectiveness. Future research should focus on these factors to maximize PBL's impact on mathematical literacy.

The study contributes significantly to mathematics education theory and the application of PBL, supporting the idea that PBL improves students' conceptual understanding, critical thinking, and mathematical literacy when aligned with appropriate learning strategies. It also strengthens constructivist theory, as students actively construct understanding through real-world problem-solving, as proposed by (Vygotsky, 1978). The findings align with Wanahari et al. (2022) on Discovery Learning, emphasizing that students grasp mathematical concepts better through self-discovery.

Additionally, the meta-analysis informs the development of more effective learning models, especially by integrating PBL with scaffolding, digital technology, and real-world problems. It highlights the effectiveness of contextualized, real-life problems over academic problems, suggesting the potential for ethnomathematics-based PBL rooted in students' culture and daily lives. This study enhances the literature on factors influencing PBL effectiveness. Key findings show that education level, students' initial ability, intervention duration, and teachers' readiness significantly impact PBL success. These insights help optimize and adapt PBL for better learning outcomes.

Overall, this meta-analysis strengthens the empirical evidence for PBL’s effectiveness in improving mathematical literacy and suggests new directions for developing adaptive learning strategies. It demonstrates that PBL is more effective when combined with differentiated instruction, technology use, and culturally relevant problems. This research provides a foundation for innovation in mathematics curriculum and pedagogy at various educational levels. The findings offer valuable insights for teachers, educators, and curriculum developers to enhance PBL's application in mathematics, with practical recommendations to increase its effectiveness in improving students' mathematical literacy.

Teachers and educators must tailor PBL to student characteristics, such as learning styles, to ensure effective concept comprehension. The study shows that visual learners benefit from graphical representations and digital animations, while auditory learners need more group discussions and verbal explanations Ornawati et al. (2023).

PBL problems should be real-world based, allowing students to connect mathematical concepts to daily life (Rehman et al., 2023). This meta-analysis found that studies using real-life problems had higher effect sizes than those using academic problems without context. Teachers can design problems based on social, cultural, or environmental phenomena, such as financial management or statistical data analysis (Bissett-Johnson & Radcliffe, 2021; Loyens et al., 2008; Mann et al., 2021; Zotou et al., 2020).

Digital technologies can enhance PBL by offering interactive visualizations and helping students explore solutions more deeply (O’Brien et al., 2019). Studies in this meta-analysis show that PBL supported by tools like GeoGebra, Desmos, or LMS tend to yield better results (Al-Fitriani et al., 2023; Husna & Kurniasih, 2023; Priyonggo et al., 2021). Thus, developing digital-based PBL is an innovative strategy to improve mathematical literacy (Chua et al., 2022).

Despite showing PBL’s positive impact on mathematical literacy, this meta-analysis has limitations, such as a limited sample size and scope. Many studies focused on junior and senior high school students, with less research on PBL in primary or tertiary education Farhan et al. (2021), limiting the generalizability of the findings. Additionally, most PBL interventions were short-term, often conducted in just a few sessions, and may not capture the long-term effects on students' critical thinking and mathematical literacy (Ertmer & Glazewski, 2024).

Another factor that was not fully analyzed in this study is the influence of external variables, such as students' learning motivation, socioeconomic background, as well as the role of parental and teacher support in problem-based learning. Some studies show that students with high intrinsic motivation are better able to adapt to PBL, while students with low motivation or less accustomed to independent learning may have difficulty in adjusting to this method (Siregar & Narpila, 2023). Therefore, not all students can benefit the most from PBL with the same level of effectiveness.

In addition, differences in research design and analysis methods among the studies analyzed may also be a factor affecting size heterogeneity (Hönekopp & Linden, 2022). Studies that use more comprehensive measurement instruments, such as real-world problem-solving-based mathematical literacy tests, tend to produce higher effect sizes compared to studies that only use standardized academic questions (Andini & Siregar, 2024). Therefore, non-uniformity in measurement methods and research design may affect the consistency of the results of this meta-analysis

Conclusion

This meta-analysis confirms that Problem-Based Learning (PBL) significantly enhances students' mathematical literacy, with a large effect size of 1.165, highlighting its role in fostering active problem solving, conceptual understanding, and critical thinking. However, its effectiveness varies depending on moderating factors such as learning styles, prior knowledge, instructional time, and problem characteristics. While PBL tends to be more effective at the junior high level, the difference compared to high school is not statistically significant, indicating the need for further investigation. Future research is encouraged to: (1) examine the long-term impact of PBL on mathematical literacy and critical thinking; (2) explore deeper moderating factors such as motivation, teacher roles, and school readiness; (3) integrate digital tools like GeoGebra, AR, and LMS into PBL; (4) assess PBL effectiveness across educational levels; and (5) compare the impact of contextual versus academic problems in improving mathematical literacy.

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Conflicts of Interest

The authors declare no conflict of interest regarding the publication of this manuscript. In addition, all ethical considerations, including plagiarism, research misconduct, data fabrication and/or falsification, redundant publication and/or submission, and data integrity—have been fully addressed and fulfilled by the authors in accordance with international academic publication standards.

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Author Contributions

Ahmad Gufron: Conceptualization, methodology, data analysis, data extraction, original draft writing, and visualization. **Wardono**: Validation, supervision, and manuscript review and editing. **Isti Hidayah and Ardhi Prabowo**: Validation, theoretical guidance, supervision, and critical revisions. **Scolastika Mariani**: Data curation, provision of resources, and literature screening.

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