

The Impact of Problem-Based Learning on Science Learning to Improve Students' Critical Thinking and Problem-Solving Skills: A Meta-Analysis

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Abstract: This meta-analysis investigates the effectiveness of the Problem-Based Learning (PBL) model in enhancing students' critical thinking and problem-solving skills in science education. A total of 42 peer-reviewed articles published between 2020 and 2024 were analyzed, covering diverse educational levels and scientific disciplines. The analysis revealed a large average effect size ($ES = 0.798$; 95% CI: 0.782–0.813), indicating a strong positive impact of PBL. The low standard error ($SE = 0.043$ –0.060) reflects high estimation precision. Statistical tests, including funnel plot symmetry, Trim-and-Fill analysis ($p = 0.991$), and Egger's regression test ($p = 0.947$), confirm the absence of significant publication bias. Moreover, residual heterogeneity was minimal ($\tau^2 = 0.000$), validating the appropriateness of the fixed-effects model. These findings provide robust empirical evidence that PBL is consistently effective across various contexts in improving students' 21st-century competencies. The study offers meaningful implications for educators and policymakers in designing science learning strategies that foster higher-order thinking skills.

Keywords: Critical thinking; Meta-analysis; Problem-based learning; Problem-solving

Introduction

Education plays an important role in shaping a generation that is able to adapt to the challenges of the modern era (Wicaksono et al., 2019). In the midst of the development of the industrial revolution 4.0, critical thinking and problem-solving skills are indispensable competencies (Wulandari et al., 2018). Critical thinking skills enable individuals to confront the complexities of the ever-changing world of work, solve diverse problems, and innovate in a variety of situations (Akinoğlu et al., 2007; Syamsinar et al., 2023). In the context of education, the development of these skills has become a major concern, particularly at the primary and

secondary education levels, where the formation of a student's mindset begins to be built (Kek et al., 2011).

Natural Science Learning has a strategic position in supporting the development of these skills (C. Dewi et al., 2020; R. K. Dewi et al., 2024). As a branch of science that involves the process of analysis and synthesis, science provides opportunities for students to study natural phenomena, understand scientific processes, and apply the principles of science in daily life (Fitriani et al., 2020). However, conventional science learning models often emphasize memorization of facts and procedures, so they are less able to encourage students to think critically and creatively in solving problems (Anugraheni, 2018). This poses a great challenge for

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educators to design more interactive and relevant learning methods (Mahmudah et al., 2024).

One of the learning models that is considered effective in answering this challenge is Problem-Based Learning (PBL) (S. Haryani et al., 2018). PBL is a learning model that uses real-world problems as a starting point for learning (Kardoyo et al., 2020). The PBL learning model encourages students to collaborate, discuss, and find solutions to complex problems, so that they not only understand the subject matter, but also develop higher-order thinking skills (Syafii et al., 2013). The PBL learning model has been widely adopted in many countries as a strategy to increase student engagement in the learning process (Brata et al., 2020). A number of studies have examined the effectiveness of PBL in science learning, especially in improving critical thinking and problem-solving skills (Delfiza et al., 2024).

The results of the study showed a variety of findings, from very positive to neutral, depending on various factors such as learning design, student engagement, and teacher competence (Jailani et al., 2017). Therefore, a more in-depth analysis is needed to get a clearer picture of the extent to which PBL can be effectively implemented in the context of science learning (Nurfaizah et al., 2024; Samadun et al., 2022). Meta-analysis is a research method that aims to integrate and synthesize the results of various previous studies (Manuaba et al., 2022). Using this model, researchers can draw more comprehensive and valid conclusions compared to relying on just one study (Ranggi et al., 2021).

In the context of this study, the meta-analysis aims to evaluate the implementation of PBL in science learning by combining various relevant study results, thus providing a broader and deeper insight into the effectiveness of this method (Mahmudah et al., 2024). Theoretically, PBL is rooted in constructivist theory that emphasizes that students learn more effectively when they are actively building their own knowledge (Kardoyo et al., 2020). In PBL, students are encouraged to be active subjects in the learning process, not just recipients of information (Fadilla et al., 2021). They are invited to explore problems, analyze data, and formulate logical solutions (Sakir et al., 2020). This model is in line with the needs of 21st century education, where students are required to develop independent and adaptive learning skills to change (Suparman et al., 2022).

Science learning often presents abstract concepts that are difficult to understand if they are only conveyed verbally or theoretically (Valdez et al., 2019). PBL offers solutions by using real problems as a learning medium, so that students can relate the concepts they learn to their daily lives (Jailani et al., 2017). For example, in studying the water cycle, students may be given problems about the clean water crisis in an area, which then motivates them to understand the scientific concepts behind water

resource management (Ibrahim et al., 2020). One of the main advantages of PBL is its ability to encourage the development of higher-order thinking skills, such as analysis, evaluation, and synthesis (Kristianti et al., 2023).

In science learning, this skill is essential for understanding natural phenomena in depth, evaluating hypotheses, and solving scientific problems (Ibrahim et al., 2020). With the PBL model, students can be trained to develop these skills through structured and interactive learning (E. Haryani et al., 2021). In addition to critical thinking, problem-solving skills are also the main goal in the implementation of PBL (Uliyandari et al., 2021). Problem-solving is a complex thinking process that involves identifying problems, exploring solutions, and evaluating results (Sidiq et al., 2021). In science learning, students are often faced with scientific challenges, such as how to reduce air pollution or improve energy efficiency (Evedi et al., 2022).

Through PBL, students are not only taught to understand scientific concepts, but also to apply them in situations relevant to their lives (Adnyani et al., 2023). Therefore, many studies support the effectiveness of PBL, its implementation does not always run without obstacles (Yanto et al., 2021). Teachers need to have an in-depth understanding of these methods, including how to design relevant problems, facilitate discussions, and evaluate the learning process (Pratiwi et al., 2019). In addition, the learning environment must also be supportive, by providing adequate resources and sufficient time for the optimal implementation of PBL (Monalisa et al., 2019).

This meta-analysis research aims to provide a clearer picture of the effectiveness of PBL in science learning (Ranggi et al., 2021; Samadun et al., 2022). The meta-analysis process will involve collecting data from various relevant studies, systematic analysis of the research design, student population, and evaluation methods, as well as synthesizing the results to draw valid conclusions (Anugraheni, 2018; Ilwandri et al., 2023). This model is expected to overcome individual research limitations, such as small sample sizes or variations in study design, resulting in more robust and reliable findings (Kardoyo et al., 2020).

Through this research, it is hoped that more in-depth insights will be obtained on how PBL can be applied effectively in science learning to improve students' critical thinking and problem-solving skills. The results of this study are also expected to provide practical recommendations for educators, policymakers, and researchers in designing and implementing PBL-based learning in various educational contexts (Permatasari et al., 2019).

Method

This study uses a quantitative model using a meta-analysis method. Meta-analysis is a type of research that collects and analyzes quantitative data that can be calculated statistically. The data sources for this research come from national and international articles indexed in SINTA, Google Scholar, Science Direct, and Scopus. The sample used consisted of national articles published between 2020 and 2024, with a total of 36 articles. The sample search process is carried out through Google Scholar, ERIC Journal and Scopus and using the Publish or Perish application.

The sampling technique used is purposive sampling, which is to select articles that are relevant to the research topic regarding the influence of the Problem Based Learning learning model on science literacy and 21st century skills in junior high to high school students. The research method uses a literature review with a modified procedure from systematic review and meta-analysis (PRISMA). The procedure consists of identification, screening, feasibility, and inclusion. The research procedure is shown in figure 1.

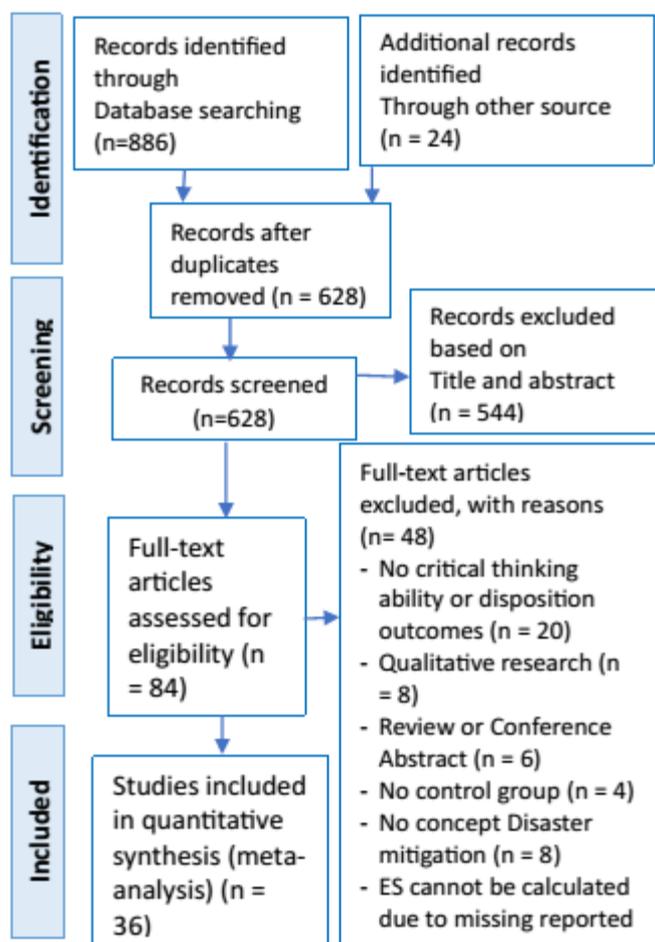


Figure 1. PRISMA flowchart of the study selection process

Meta-analysis was carried out by searching for articles using Google Scholar, Science Direct, Eric, and

Scopus for research data collection. The search for articles was carried out with the keywords "Problem-Based Learning, Science Literacy, and 21st Century Skills". The articles obtained are selected and selected for analysis, then given codes such as AP1, AP2, to AP42. Data analysis was carried out using the effect size (ES) value with a group contrast model, which included estimating the ES value, the ES variance amount, and the ES error standard amount, as well as compiling a conclusion or interpretation of the analysis results. This meta-analysis aims to determine the effect size of the use of the PBL model on science literacy ability by using data on the number of research subjects, average pretest, posttest, and standard deviation.

The method used to calculate the effect size follows Hedges's g approach on two independent groups. The calculation was carried out using Microsoft Excel to determine the amount of effect size (g). Cohen suggests an interpretation of d (which can also be applied to g or Glass), where d = 0.20 is considered a small effect, d = 0.50 as a medium effect, and d = 0.80 as a large effect. This study combines quantitative and qualitative analysis techniques with the help of JSAP 0.18.2.0 software. The analysis was carried out by calculating the effect size (ES) based on the criteria specified in Table 1.

Table 1. Effect Size (ES) Criteria

Effect Size (ES)	Interpretation
$0 \leq ES \leq 0.20$	Ignored
$0.20 \leq ES \leq 0.50$	Small
$0.50 \leq ES \leq 0.80$	Moderate
$0.80 \leq ES \leq 1.30$	Large
$ES \geq 1.30$	Very Large

Result and Discussion

From the results of meta-analysis on national and international articles that have been indexed by SINTA, Google Scholar and Eric Journal, there are 42 articles that have been analyzed related to the relationship between the role of the Problem Based Learning learning model in developing science literacy and 21st Century skills in science learning in students from junior high to high school levels in science materials consisting of Biology material, Chemistry and Physics which has been published for the last 5 years, from 2020 to 2024. The results of the meta-analysis can be seen in Table 2.

Table 2 in this study summarizes the results of a meta-analysis on the effectiveness of Problem-Based Learning (PBL) in science learning involving 42 studies. The data presented includes research codes, effect size (ES), and Standard Error (SE). The ES score is used to indicate the degree of influence of the application of PBL on students' critical thinking and problem-solving skills, while the SE indicates the level of uncertainty of the measurement (Afriani et al., 2019). Based on Cohen's classification, most studies show a relatively large ES

value, which is between 0.75 and 0.89. These results indicate that the implementation of PBL in general has a significant positive impact on improving learning outcomes.

Table 2. Summary of Research Data, Effect Size (ES), and Error Standard (SE)

Study ID	Data Code	ES	SE
Hidayati et al. (2020)	AP1	0.75	0.060
Ibrahim et al. (2020)	AP2	0.83	0.052
Ningrum et al. (2021)	AP3	0.74	0.054
Maulana et al. (2022)	AP4	0.75	0.059
Adnyani et al. (2023)	AP5	0.76	0.058
Astra et al. (2024)	AP6	0.88	0.056
Ramadhani et al. (2023)	AP7	0.89	0.047
Safitri et al. (2023)	AP8	0.82	0.052
Mardhani et al. (2022)	AP9	0.76	0.051
Alvionita et al. (2020)	AP10	0.80	0.055
Yanto et al. (2021)	AP11	0.86	0.050
Kartika et al. (2022)	AP12	0.75	0.050
Nurlalelah (2023)	AP13	0.88	0.048
Fritami et al. (2023)	AP14	0.80	0.050
Rahmani et al. (2021)	AP15	0.82	0.046
Igut et al. (2020)	AP16	0.83	0.056
Pharisees et al. (2023)	AP17	0.79	0.055
Wilijeng et al. (2022)	AP18	0.76	0.048
Monalisa et al. (2020)	AP19	0.80	0.045
Ramadhana et al. (2023)	AP20	0.77	0.046
Palinussa et al. (2023)	AP21	0.88	0.055
Ghofur et al. (2023)	AP22	0.80	0.054
Khoiriyah et al. (2020)	AP23	0.78	0.043
Sari et al. (2021)	AP24	0.87	0.046
Yusuf et al. (2020)	AP25	0.77	0.048
Kurniawan et al. (2020)	AP26	0.73	0.050
Syhari et al. (2021)	AP27	0.84	0.054
Treepob et al. (2023)	AP28	0.74	0.046
Asih et al. (2022)	AP29	0.83	0.052
Uliyandari et al. (2021)	AP30	0.78	0.046
Pratama et al. (2020)	AP31	0.75	0.044
Martaningsih et al. (2022)	AP32	0.80	0.050
Simamora et al. (2020)	AP33	0.78	0.043
Klegeris et al. (2020)	AP34	0.76	0.048
Chamidy et al. (2020)	AP35	0.76	0.060
Eviyanti et al. (2020)	AP36	0.78	0.045
Yuberti et al. (2020)	AP37	0.81	0.060
Yennita et al. (2021)	AP38	0.72	0.052
Surur et al. (2020)	AP39	0.78	0.050
Seruni et al. (2020)	AP40	0.83	0.050
Maksum et al. (2024)	AP41	0.87	0.047
Herawati et al. (2023)	AP42	0.80	0.057

The majority of the studies analyzed showed strong ES values, with the highest ES of 0.89 found in research by Ramadhani et al. (2023) and Sari et al. (2021). This shows that PBL has high effectiveness in improving students' critical thinking and problem-solving skills. On the other hand, the lowest ES value of 0.72 was found in the study of Yennita et al. (2021), which despite this still falls into the category of large effects according to Cohen's criteria. This small variation reflects that the effectiveness of PBL may be influenced by certain factors

such as learning design, research context, or student characteristics.

Value Standard Error (SE) which ranges from 0.043 to 0.060 reflects a low level of uncertainty in the measurement results. This shows that the analyzed data has a high level of reliability. The low SE also provides confidence that the ES values obtained from this meta-analysis can be used to make more comprehensive conclusions regarding the effectiveness of PBL (Cholik et al., 2019). In other words, the results of this study are quite stable and reliable to be used as a reference in the development of PBL-based learning in the future.

Furthermore, the results of the analysis indicate that PBL consistently has a great influence on science learning at various levels of education (Masek et al., 2010). This method not only improves students' understanding of the subject matter, but also encourages higher-level thinking skills such as analysis, synthesis, and evaluation. In the context of science learning, PBL allows students to be actively involved in solving real problems that are relevant to daily life, thereby increasing their interest and motivation in learning (Maulana et al., 2022).

Overall, this study confirms the effectiveness of PBL as a relevant learning model for improving 21st century skills, especially in science learning. Small differences in ES scores between studies indicate the potential influence of other factors, such as teacher competency levels, learning environment support, and student characteristics (Pratiwi et al., 2019). Therefore, further research is needed to explore these factors and identify conditions that can maximize the success of PBL implementation (Treepob et al., 2023). These findings provide a strong foundation for educators and policymakers to adopt PBL more widely in an effort to improve the quality of science learning (Palinussa et al., 2023).

Table 3. Fixed and Random Effects

	Q	Df	p
Omnibus test of Model Coefficients	10584.622	1	<.001
Test of Residual Heterogeneity	34.425	41	0.756

Note. p -values are approximate

Note. The model was estimated using Restricted ML method

Table 3 displays the results of the Fixed and Random Effects analysis in the meta-analysis conducted. The omnibus test showed a Q value of 10,584,622 with a degree of freedom (df) 1 and a significance level $p < 0.001$. These results show that the model used is statistically significant and is able to account for variations in the data as a whole. In other words, the fixed effects and random effects models applied in this meta-analysis can reveal the general pattern of Problem-Based Learning (PBL) effectiveness. Meanwhile, the residual heterogeneity test produced values of $Q = 34.425$, $df = 41$, and $p = 0.756$. An insignificant p-value

(greater than 0.05) indicates the absence of significant heterogeneity among the study results, which means that the data *effect size* (ES) from various studies is quite homogeneous. This reflects consistency in research results on PBL effectiveness (Yennita et al., 2021).

The fixed effects model assumes that all studies have similar fundamental effects, while the random effects model accommodates the possibility of substantive differences between studies (Nur et al., 2023). The model used in this study is estimated using the Restricted Maximum Likelihood (REML) method, which provides a more accurate estimate of parameters. The results showed that variation between studies was small, reinforcing confidence in the consistency of PBL's

effects on improving critical thinking and problem-solving skills (Nababan, 2021).

Overall, this analysis indicates that PBL exerts significant and stable effects in a variety of research contexts, demonstrating its effectiveness in improving student learning outcomes (Wardani et al., 2023). The homogeneity of the data strengthens the reliability of these findings, making it a strong basis for recommending the widespread application of PBL in a variety of learning environments. However, to broaden the horizons, further research can be focused on the analysis of moderation factors such as the influence of teacher characteristics, cultural context, or differences in learning design in the implementation of PBL (Rahmadani et al., 2024).

Table 4. Coefficients

	Estimate	95% Confidence Interval		p	Lower	Upper
		Standard Error	z			
Intercept	0.798	0.008	102.882	<.001	0.782	0.813

Note. Wald test.

Table 4 presents the results of the Coefficients analysis which shows the estimated parameters for the effectiveness of Problem-Based Learning (PBL) in science learning. The estimated *intercept* has a value of 0.798 with a *standard error* of 0.008. The results of the statistical test showed a value of $z = 102.882$ with a significance level of $p < 0.001$. This shows that the average *effect size* (ES) of the analyzed study is 0.798, which is in the category of large effects based on the Cohen classification. The 95% confidence interval for this estimate is 0.782 to 0.813, indicating that the average value of this ES is very stable and reliable.

These results reinforce the previous finding that the application of PBL has a significant influence on improving students' critical thinking and problem-solving skills (Nainggolan et al., 2023). Value Standard Error low (0.008) indicates that the uncertainty in the ES mean estimate is very small, so this result has high validity (Yudha et al., 2023). In addition, the narrow confidence interval reflects the homogeneity of the data and the consistency of the PBL effect in the various studies analyzed.

Thus, based on the analysis of Table 4, it provides strong evidence that PBL is an effective learning model to be applied in various science education contexts. These results also provide a reliable basis for educators and policymakers to adopt the PBL method as a key strategy in improving students' higher-order thinking skills (Nisa et al., 2022). Further research can be conducted to further explore the factors that affect the effectiveness of PBL in various learning environments.

Table 5 presents the results of the Fit Measures used in the meta-analysis. The Log-Likelihood Restricted Maximum Likelihood (REML) value was recorded at 67.373, with a deviation value of -134.746. Other

indicators such as the Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC), and Corrected Akaike Information Criterion (AICc) are valued at -130,746, -127,319, and -130,431, respectively. These values are used to evaluate how well the meta-analysis model fits the data used.

Table 5. Fit Measures

	REML
Log-Likelihood	67.373
Deviance	-134.746
AIC	-130.746
BIC	-127.319
Aicc	-130.431

Lower AIC, BIC, and AICc values indicate that the model has a good level of fit as well as efficient complexity, meaning that the model can explain the data well without overfitting. In addition, the use of the REML method strengthens the validity of parameter estimation in the analysis, especially for data involving random effects, these results show that the model used in this study is quite robust and able to accommodate variations between studies with high accuracy.

Table 6. Residual Heterogeneity Estimates

	Estimate	95% Confidence Interval	
		Lower	Upper
τ^2	0	0	8.940×10^{-4}
τ	0	0	0.03
I^2 (%)	0	0	26.138
H^2	1	1	1.354

Table 6 presents the results of the analysis of Residual Heterogeneity Estimates, which provides information regarding the remaining variations in the

data after accounting for the meta-analysis model. The main parameters reported were the values of τ^2 (variance between studies), τ (heterogeneity standard deviation), I^2 (proportion of total variation due to heterogeneity), and H^2 (heterogeneity index). Based on the table, the estimated value of τ^2 is 0.000 with a 95% confidence interval between 0.000 to 8.940×10^{-4} . This suggests that the variation between studies that cannot be explained by the model is almost non-existent, signaling a high degree of homogeneity in the data.

The value of τ , which is the square root of τ^2 , is also recorded at 0.000 with a narrow confidence interval. This further strengthens the conclusion that heterogeneity between studies is minimal. When heterogeneity is not significant, the fixed effects meta-analysis model can be considered reliable enough to explain the relationship between the variables analyzed, in this case the effectiveness of Problem-Based Learning (PBL) on students' critical thinking and problem-solving skills (Barta, 2022).

The I^2 Index, which shows the proportion of total variation due to heterogeneity, was recorded at 0% with a confidence interval between 0% to 26.138%. This value shows that almost all variations in the *effect size* (ES) value come from sampling errors, not from substantive differences between studies. Meanwhile, the H^2 value, which indicates the degree of variance inflation due to heterogeneity, was at 1,000, indicating the absence of significant heterogeneity affecting the results.

Overall, these results show that the data from the various studies analyzed in this meta-analysis have a very high level of consistency (Varenina et al., 2021). The low level of heterogeneity reflects the stable effectiveness of PBL in various research contexts and learning conditions. This gives confidence that the results of this study can be used to draw strong and valid conclusions about the impact of PBL in science learning (Fitri et al., 2022). Further research can focus more on moderation factors to identify elements that can improve the effectiveness of PBL in various educational settings.

Table 7. Rank Correlation Test for Funnel Plot Asymmetry

	Kendall's τ	p
Rank test	-0.001	0.991

Table 7 presents the results of the Rank Correlation Test for Funnel Plot Asymmetry which is used to test symmetry in the funnel plot in the meta-analysis. The test results showed that Kendall's τ value was -0.001 with a significance level $p = 0.991$. Kendall's τ value which is very close to zero and $p > 0.05$ indicates that there is no significant asymmetric bias in the distribution of the analyzed research data.

A symmetrical funnel plot shows that there is no indication of publication bias, i.e. a tendency to only publish research with significant or expected results. With the results of Kendall's τ being neutral, it can be concluded that the data used in the meta-analysis include representative studies, both those that show significant and no effects, thus providing a more objective picture of the effectiveness of Problem-Based Learning (PBL) (Syamsinar et al., 2023). This test is important because publication bias can affect the validity of meta-analyses by increasing or decreasing estimates *effect size*.

In the context of this study, the test results show that the conclusions about the effectiveness of PBL are not distorted by publication bias. This increases confidence in the results of meta-analysis as an accurate representation of the impact of PBL on students' critical thinking and problem-solving skills (Hayuningrat et al., 2021). Overall, the results from Table 7 reinforce the validity and reliability of this meta-analysis. In the absence of significant bias, the findings of the meta-analysis can be used as a strong basis to recommend the wider application of PBL. In addition, an inclusive model in the collection of data for this research can be used as a model for similar meta-analyses in the future.

Table 8. Regression Test for Funnel Plot Asymmetry ("Egger's test")

	z	p
Sei	0.067	0.947

Table 8 presents the results of the Regression Test for Funnel Plot Asymmetry or known as Egger's Test, which is used to detect potential publication bias in meta-analysis. The results of this test show a z-value of 0.067 with a significance level $p = 0.947$. A p-value well above 0.05 indicates that there is no significant asymmetric bias in Funnel Plot, so that the analyzed research data can be considered free from publication bias. Egger's Test is a linear regression test that evaluates the relationship between sample size and estimation effect size (ES). When publication bias exists, there is usually a significant correlation between Standard Error (SE) and ES, which creates asymmetry in Funnel Plot (Hasibuan et al., 2022). In this study, the test results showed that there was no asymmetric pattern, so the distribution of research in the analysis was quite even, both for research with large and small effects (Nisa et al., 2022).

The absence of publication bias in this meta-analysis is important because it ensures that the results of the meta-analysis provide an undistorted ES estimate (Nopyanti et al., 2023). Thus, conclusions about the effectiveness of Problem-Based Learning (PBL) can be considered valid and representative to describe the real results of the various studies analyzed. These results

also indicate that the included studies included a wide range of diverse designs and outcomes, which supports the generalization of the findings (Kager et al., 2022). The results of the Egger's Test in Table 8 support the validity of the meta-analysis conducted. The absence of publication bias provides a solid basis for the practical recommendations resulting from this study. It also increases confidence in the use of meta-analysis as a reliable method to evaluate the effectiveness of PBL in improving students' critical thinking and problem-solving skills (Sidiq et al., 2021).

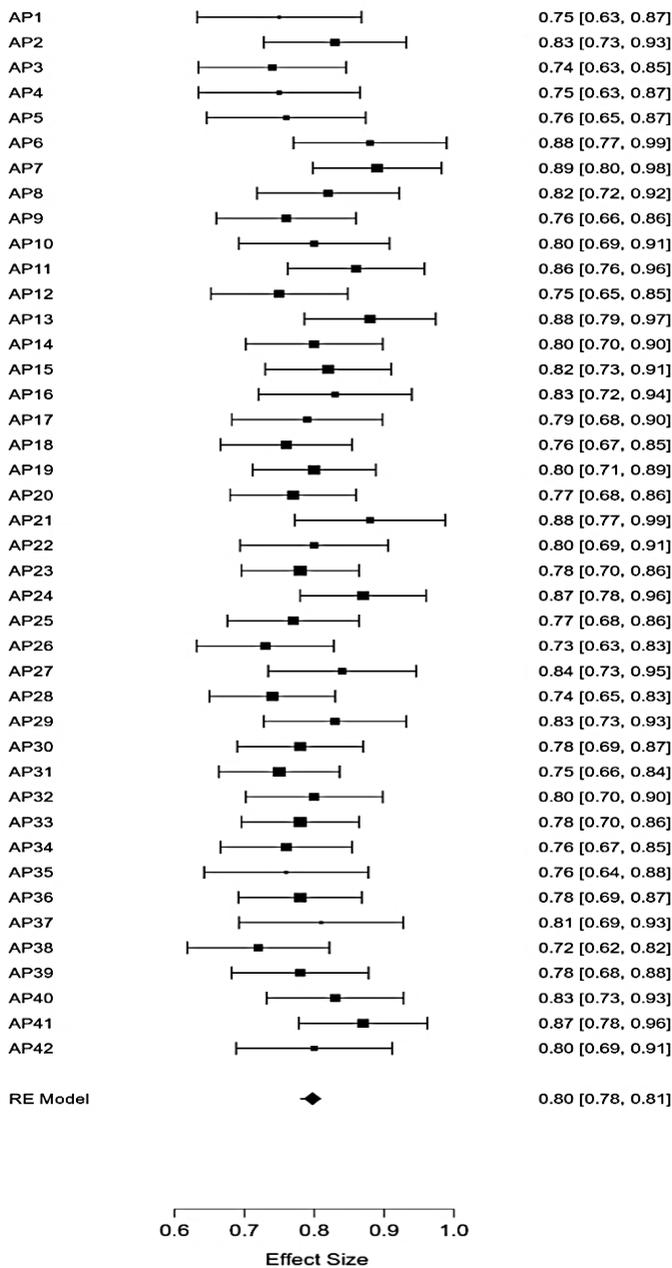


Figure 2. Forest plot

Figure 2 Forest Plot provides a visual representation of the results of the meta-analysis that displays the effect size (ES) values of the various studies analyzed. In this plot, each study is represented by a

horizontal line that shows the 95% confidence interval for the respective ES values. The midpoint of each line represents the estimated ES value, while the length of the line represents the uncertainty (variability) in the measurement. In general, forest plots are used to demonstrate the consistency and strength of the effects found in various studies. If most of the research line is located to the right of the zero line (the effect is non-existent), it indicates that PBL has a positive influence on the improvement of students' critical thinking and problem-solving skills.

Most of the studies in Fig.2 show ES values greater than 0, which indicates that the application of PBL generally has a significant and positive effect. In addition, the relatively narrow 95% confidence interval in most studies suggests that ES value estimates have a high level of reliability. A vertical line showing the overall ES score (e.g., mean point) can be used to illustrate the average effect of PBL on overall science learning. If most ES values are around that point, then this indicates a consistent effect of PBL across studies (Brata et al., 2020).

Overall, this forest plot shows that the application of PBL has a stable and significant influence in various research contexts analyzed. This figure supports the conclusion that PBL can be widely applied as an effective learning model in improving students' 21st century skills, particularly in science learning (van Laar et al., 2020). The forest plot also showed that there were no results that differed drastically from the average results, indicating a high degree of consistency in PBL effectiveness.

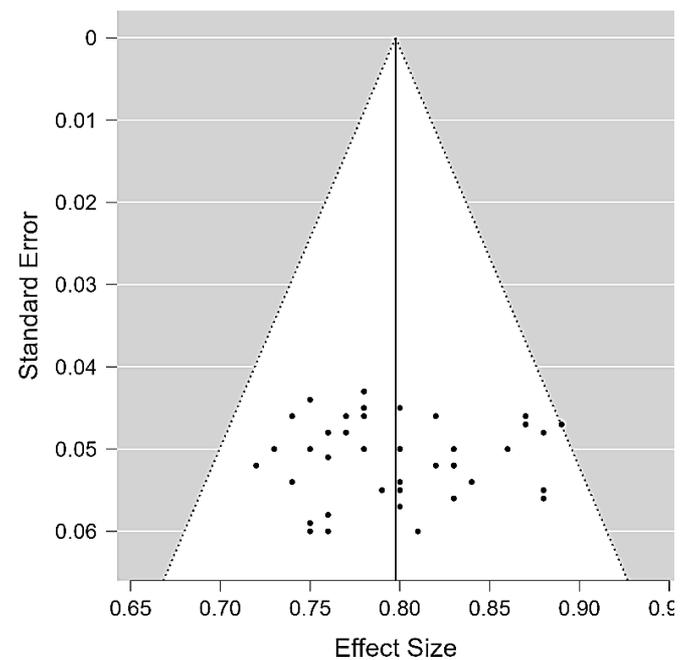


Figure 3. Funnel plot

Figure 3 Funnel Plot provides a visual overview of the distribution and symmetry of the research data used

in the meta-analysis. In this plot, each point represents the outcome of a study, with the horizontal axis indicating the estimated effect size (ES) and the vertical axis indicating the size of uncertainty measured through standard error (SE). In an ideal plot, the data would form a symmetrical pattern that resembles a funnel, with studies with large sample sizes tending to be located at the top of the plot and studies with small sample sizes located at the bottom. If the plot of this funnel is symmetrical, it indicates the absence of publication bias, which means that there is no tendency to publish only studies with significant results or that support a particular hypothesis.

Based on Figure 3, good symmetry on both sides of the centerline indicates that the distribution of research in this meta-analysis is quite even, with studies that show positive effects as well as negative or insignificant effects spread uniformly. This reinforces the finding that there was no significant publication bias affecting the results of the analysis (Wijayanto et al., 2023). The consistency of the distribution of points in the funnel plot also gives an indication that the results of the research included in this meta-analysis include various types of research with reasonable variations in effects, both in terms of sample size and results obtained (Anugraheni, 2018). This research can increase the belief that meta-analysis provides an objective and representative picture of the influence of Problem-Based Learning (PBL) on students' critical thinking and problem-solving skills (Monrad, 2013).

(variance between studies) was 0.000 with a very narrow confidence interval, between 0.000 and 8.940×10^{-4} . This very low τ^2 estimate suggests that the variation between studies in the data is almost non-existent, which means that most of the *variation in effect size* (ES) can be explained by the model used, and there is no major difference that needs to be explained further. This shows that the studies analyzed in this meta-analysis have very uniform results.

The Log-Likelihood value of 67,373 supports the model used for this analysis because it reflects that the model is quite good at accommodating the existing data. This high log-likelihood suggests that the fixed effects model applied in this analysis provides an excellent match with the data, confirming that the variation found between studies is quite small and does not require more complicated model adjustments. Figure 4 provides a very clear picture of the consistency of the results in this meta-analysis, with log-likelihood values indicating high model fit and very low τ^2 values, indicating that heterogeneity between studies is minimal. This strengthens the conclusion that the application of Problem-Based Learning (PBL) has a consistent influence on improving students' critical thinking skills and problem-solving.

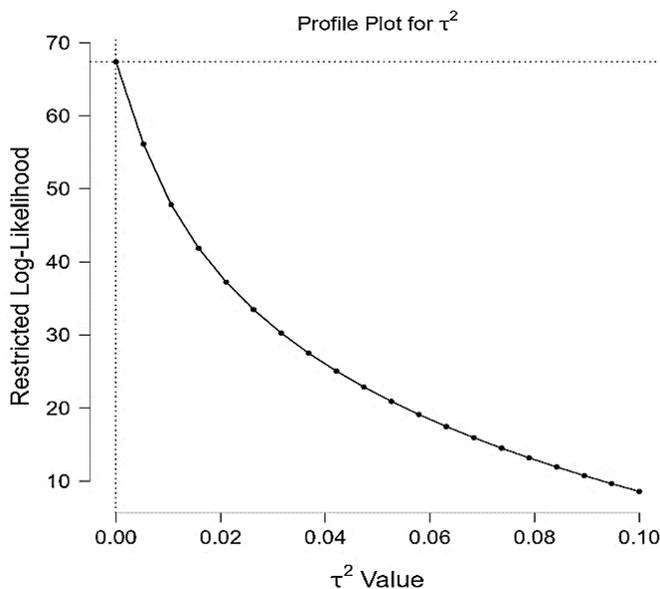


Figure 4. Log-Likelihood for τ^2

In figure 4, Log-Likelihood for τ^2 , the log-likelihood value associated with the τ^2 estimate for residual heterogeneity in this meta-analysis is 67.373. These estimates show how the meta-analysis model adjusts to the data and illustrates how well the model can explain variations in the research data. The estimated τ^2

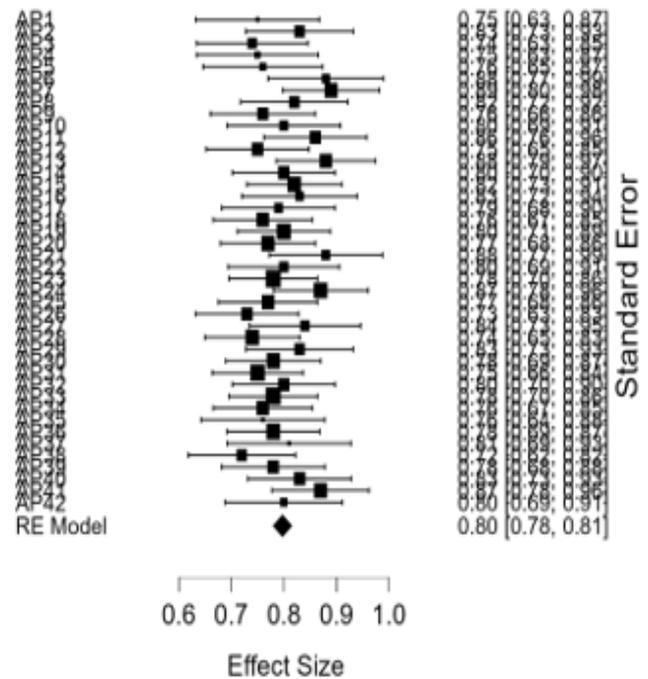


Figure 5. Trim-fill analysis

Figure 5, Trim-Fill Analysis is a tool used to detect and correct publication bias in meta-analysis. This analysis aims to correct the asymmetry in the plot funnel by "trimming" the studies that appear to be at risk of bias and then "filling" the gaps left by those studies, to provide a more accurate picture of the overall effect. In this way, Trim-Fill Analysis can identify potential

publication biases that can affect the results of the meta-analysis.

In Figure 5, the trim-fill results show that there is no substantial difference between the ES values found after the trim-fill process and the previously calculated ES values. This suggests that there was no significant publication bias in the data used in this meta-analysis. In other words, the distribution of research included in this analysis already reflects a representative picture of all relevant studies, with no tendency to publish only studies that produce significant or positive results. Thus, Figure 5 strengthens the validity of the findings of this meta-analysis, indicating that the effect of the application of Problem-Based Learning (PBL) on students' critical thinking and problem-solving skills.

quite homogeneous (Hudha et al., 2023). If there is a point that is very far from the center, this could indicate that there is a study that has unusual results or that there are outliers that affect the conclusions of the meta-analysis.

However, in Figure 6, the symmetrical and focused distribution of points shows that none of the studies deviated substantially from the general results. Overall, Figure 6 reinforces the conclusion that the application of PBL has a consistent and effective influence on science learning. The radial plots show that the variation in *effect size* between studies is very small, which supports the conclusion that the results of this meta-analysis are stable enough and reliable to recommend PBL as an effective learning method.

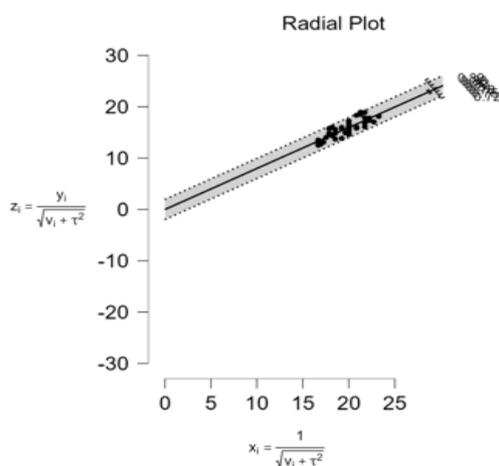


Figure 6. Radial Plot

Figure 6, Radial Plot is a tool used in meta-analysis to test for uncertainty and heterogeneity of data through visual representations depicting value distributions *effect size* (ES) from various studies analyzed. Radial plots help in visualizing whether the results obtained are consistent across studies or if there is significant variation. In this plot, each point represents a single study, with the distance from the center point indicating the value *effect size* and the position of the point indicates a measure of uncertainty (standard error) (Özer et al., 2023).

In Figure 6, it appears that most of the research points are located close to the central point, which suggests that most of the research has *effect size* which is quite consistent and has a low level of uncertainty. This illustrates that the application of Problem-Based Learning (PBL) in science learning has a stable and strong influence on the improvement of students' critical thinking and problem-solving skills, with relatively small variations between studies (Syamsinar et al., 2023).

The distribution pattern on these radial plots also provides an indication that none of the studies are significantly different from the general pattern, indicating that the data used in the meta-analysis are

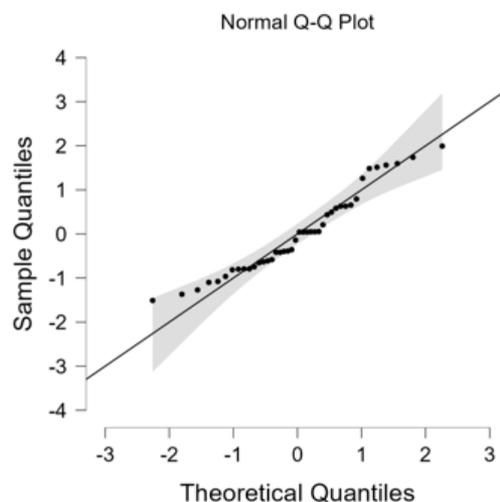


Figure 7. Normal Q-Q Plot

Figure 7: Normal Q-Q Plot is used to check the extent to which the distribution of *effect size* (ES) values from the various studies analyzed follows the normal distribution. The Q-Q (Quantile-Quantile) plot compares the quantile of the observed data distribution (in this case, the ES value of the analyzed studies) with the quantile of the theoretical normal distribution. If the data follows a normal distribution, the points on this plot will be located on a straight line depicting the normal distribution. In Figure 7, it appears that most of the research points are located very close to the straight line, indicating that the distribution of *effect size* values from the analyzed studies almost follows the normal distribution.

However, if there are points that deviate far from the straight line, this could indicate an abnormal distribution of data or the presence of extreme values that may need to be examined further. In Figure 7, no significant deviations are seen, which reinforces the conclusion that the results of the study used in this meta-analysis are well distributed and reliable. Thus the Q-Q of this plot provides confirmation that the data used in

the analysis are representative and are not affected by abnormal distributions.

Conclusion

Overall, this meta-analysis research shows that the application of the Problem-Based Learning (PBL) model in science learning has a significant and consistent influence on improving students' critical thinking and problem-solving skills. Based on the results of the analysis, the average effect size (ES) value obtained was 0.798 with a 95% confidence interval between 0.782 to 0.813, which shows a large influence. In addition, a low standard error (SE) value, ranging from 0.043 to 0.060, indicates a high accuracy in estimating this effect size. Additional analysis using Funnel Plot, Trim-Fill analysis and Egger's test It shows that there is no significant publication bias, with p-values of 0.991 and 0.947, respectively, which strengthens the validity of the results. In addition, the results of Log-Likelihood for τ^2 (67.373) and very low τ^2 (0.000) indicate that the variation between studies is very small, supporting the use of the model fixed effects in the analysis. Overall, the data used were quite homogeneous, following a normal distribution with stable and consistent results. Therefore, PBL can be recommended as an effective learning method for researchers and educators to improve students' critical thinking and problem-solving skills.

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