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Enhancing Critical Thinking Skills and Environmental Awareness through Problem-Based Learning: A Meta-Analytical Approach

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Abstract: This study aims to analyze the influence of the Problem-Based Learning model on the development of students' critical thinking skills and environmental concern through meta-analysis research. Meta-analysis was carried out on 33 relevant national and international articles. Data collection was carried out through a systematic literature search on academic databases such as Sinta, Scopus, Web of Science, Google Scholar, and Eric Journal. Based on the results of the study, it showed an increase in the average pretest score of 67.09 to 80.98 on the posttest, as well as the size effect (ES) which ranged from 0.66 to 0.89. Data shows that the application of PBL is able to improve students' analytical thinking skills while fostering awareness of environmental issues. PBL, as an authentic problem-solving-based model, has a significant positive impact with consistent results at various levels of education, both secondary and tertiary. This study also identifies factors that support the success of PBL, such as learning design, the quality of interaction between students and teachers, and the relevance of the context of the problems presented. With an average error standard of ≈ 0.05, the results of this study have a high level of reliability. These results have important implications for the development of education policies to integrate the PBL model in the curriculum to improve students' critical thinking skills and environmental concerns. This study concludes that PBL is an effective learning strategy in shaping students who are not only intelligent, but also care about environmental sustainability.

Keywords: meta-analysis, problem-based learning, critical thinking, environmental awareness.

▪ INTRODUCTION

Education is an important element in shaping a generation that is ready to face increasingly complex global challenges (Hertlein, Suresh, Brown, Davis, & Hechter, 2023). One of the main challenges faced by education systems in different parts of the world is the development of students' critical thinking skills and environmental concern (Amin, 2020). Critical thinking skills include the ability to analyze, evaluate, and formulate solutions to existing problems, while environmental concern refers to an individual's awareness and desire to preserve the environment (Hafni, Herman, Nurlaelah, & Mustikasari, 2020). These two skills are considered essential competencies in dealing with various increasingly pressing social and environmental problems. Therefore, education that is able to develop these two aspects needs to be the main focus in the context of education in the 21st century (Syamsinar, Rahman, & Dassa, 2023). In an effort to improve students' critical thinking skills and environmental concern, the right learning model is very important. One promising learning model is Problem-Based Learning, which has been proven to be effective in developing students' critical thinking skills (Loyens, 2023).

Problem-Based Learning is a learning model that focuses on authentic and relevant problem-solving, which requires students to be actively involved in the learning process (Caswell, 2019). Through PBL, students not only receive information passively, but are

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given the opportunity to identify problems, analyze data, and formulate solutions collaboratively (Vasquez & Lara, 2020). PBL also allows students to relate learning to real-world issues, which can lead to increased their awareness of environmental issues (Celeiro et al., 2021). Along with the popularity of PBL in various educational contexts, there are various findings that indicate that this model can improve students' critical thinking skills. Previous studies have shown that students who engage in problem-based learning tend to have better analytical skills, the ability to critically evaluate information, and are better able to solve complex problems (Smith, 2022). In addition, PBL also has the potential to increase students' awareness of environmental issues, as the problems solved in PBL are often related to real social and ecological challenges, such as climate change, ecosystem damage, and sustainability issues (Hafni et al., 2020).

However, although there are many studies that show the positive influence of PBL on critical thinking skills and environmental awareness, the results obtained are not always consistent (Kardoyo, 2020). Some studies show significant influence, while others show more ambiguous findings. The variability of these results shows that the effectiveness of PBL in developing these two skills can be influenced by various factors, such as learning design, educational context, and the role of educators in facilitating the learning process (Dahl, 2018). Therefore, a more in-depth and comprehensive study is needed to identify the factors that affect PBL's success in improving critical thinking skills and environmental awareness (Lohmann et al., 2020). This article aims to present the results of a meta-analysis on the influence of Problem-Based Learning on students' critical thinking skills and environmental concerns.

This meta-analysis collects and analyzes relevant research results with a focus on the influence of PBL on these two aspects. Using a systematic and quantitative model, this meta-analysis aims to provide a clearer and more comprehensive picture of the extent to which PBL can improve students' critical thinking skills and environmental awareness, as well as what factors can affect its effectiveness (Xu, Wang, & Wang, 2023). This meta-analysis process will be carried out by identifying, collecting, and evaluating the quality of relevant previous research, both from international and national journals. The research included in this analysis has certain criteria, such as a valid research design, a representative student population, and the application of a clear and structured PBL model. Furthermore, this article will analyze the effects of PBL on critical thinking skills and environmental concern using appropriate statistical techniques, resulting in a more objective and reliable understanding.

Before discussing the results of the meta-analysis, this article will review the basic concepts of Problem-Based Learning, including the main characteristics of this model, the underlying principles, and how PBL is applied in an educational context. PBL, as a model based on authentic problem-solving, requires students to work together in groups, solve complex problems, and find solutions that are relevant to real-life contexts (Mohseni, Seifoori, & Ahangari, 2020). In this case, PBL integrates various disciplines and encourages students to think critically in dealing with existing problems (Risdianto, Dinissjah, Nirwana, & Kristiawan, 2020). Therefore, PBL is believed to have great potential in improving students' critical thinking skills. Furthermore, this article will also discuss critical thinking skills and environmental concern as competencies that need to be developed in modern education (Ahmady & Shahbazi, 2020). Critical thinking skills refer to an individual's ability to think logically and analytically, as well as make decisions

based on evidence and strong reasoning. Students who have good critical thinking skills are able to evaluate information objectively and make the right decisions in dealing with various situations (Kim, Belland, & Walker, 2018).

On the other hand, environmental concern is an attitude and behavior that reflects awareness of environmental problems and a desire to participate in environmental conservation efforts (Loyens, 2023). These skills are becoming even more important given the environmental crisis the world is facing today, which requires a generation that is not only smart but also cares about the sustainability of the planet. As part of the analysis, this article will identify the factors that can influence the successful implementation of PBL in developing both skills. Some of the factors that will be examined include the design of the problems used in PBL, the quality of interaction between students and teachers, and the cultural and social context in which PBL is applied. It is important to understand that while PBL has great potential, its effectiveness is highly dependent on the contextual factors that exist within a particular educational environment (Roberto, Dell, & Kenneth, 2021). The main purpose of this article is to provide a deeper understanding of the extent to which PBL can affect students' critical thinking skills and environmental concerns. In addition, the results of this meta-analysis are expected to provide practical recommendations for educators and education policymakers in designing more effective and relevant learning strategies.

Thus, it is hoped that this research can contribute to the development of learning models that are able to overcome educational challenges in the future. This study aims to identify and analyze the influence of the Problem-Based Learning Model on the development of students' critical thinking skills and environmental concern, as well as provide a solid basis for the development of more effective educational policies and practices. Based on this description, this meta-analysis research also aims to examine how the Problem-Based Learning Model can play a role in improving students' critical thinking skills and environmental concern in the context of education (Phelan, Barrett, & Lennon, 2022). This review explores the PBL learning design applied in various selected studies, focusing on their effects on both aspects. The implementation of PBL in this study involves students at the secondary and higher education levels. Therefore, this review is expected to provide guidance in designing and implementing PBL effectively, as well as provide insight into its influence on students' critical thinking skills and environmental concerns. The main focus of this study includes:

1. How is the Problem-Based Learning model applied in learning to develop students' critical thinking skills and environmental concern?
2. What is the effect of the Problem-Based Learning model on the development of students' critical thinking skills and environmental concern?

▪ METHOD

Research Design

This study uses a meta-analysis model, which is a systematic method to collect, analyze, and synthesize data from various previous studies. This model is designed to evaluate the influence of the Problem-Based Learning Model on the development of students' critical thinking skills and environmental concern. Through meta-analysis, this study seeks to identify general patterns, relationships between variables, and factors that affect learning outcomes from various relevant studies. The selected articles include

research conducted in the last 5 years, indexed in national and international journals, and focus on secondary and higher education levels. Inclusion criteria include studies that explore the influence of PBL on students' critical thinking skills and environmental concerns. Articles that do not provide quantitative data or are irrelevant to the focus of the study are excluded from the analysis. Data analysis involves both quantitative and qualitative models. Quantitatively, the effect size was calculated to evaluate the extent to which PBL affected students' critical thinking skills and environmental concern (Quinn, 2020). This data is analyzed using relevant statistical software to get an idea of the strength of the relationship between variables. Qualitatively, the data was analyzed to identify the learning design, implementation strategy, and research context of each study. This qualitative analysis complements the quantitative findings and provides deeper insights into the design and implementation of learning (Chernikova et al., 2020).

The research procedure includes several stages: literature identification through systematic search, selection of articles based on inclusion and exclusion criteria, quantitative and qualitative data extraction, data analysis to calculate the effect of measures as well as interpretation of findings, and finally synthesis of results to answer the research objectives (Xu et al., 2023). The validity of the research is maintained by triangulation of data, while reliability is ensured through the use of standardized research protocols in data selection, analysis, and interpretation (Coppens et al., 2020). This research design is designed to produce a comprehensive empirical insight into the role and effectiveness of the Problem-Based Learning model in improving students' critical thinking skills and environmental concern. The results of this meta-analysis are expected to be a guideline in developing more effective learning strategies to improve both skills. The findings also have practical implications for educators and policymakers in designing curricula that support the development of critical thinking skills and environmental awareness among students.

Search Strategy

The search strategy in this study is carried out systematically to ensure that the literature relevant to the theme of the Problem-Based Learning Model and its influence on students' critical thinking skills and environmental concern can be comprehensively identified. The focus of this study is to explore the influence of PBL on these two skills in the context of education (Sheykhmousa et al., 2020). Literature searches are conducted through leading academic databases such as Sinta, Scopus, Web of Science, Eric Journal, and Google Scholar, which are selected for their credibility and broad scope in providing quality scientific literature. Literature searches use strategically structured keywords to cover various aspects relevant to the research. The main keywords used include "problem-based learning," "critical thinking skills," "environmental awareness," and "student potential," among other variations. This combination of keywords is formulated with Boolean operators (such as AND, OR, and NOT) to ensure search results cover a variety of perspectives without losing the main focus. For example, combinations such as "problem-based learning AND critical thinking AND environmental awareness" are used to reach out to articles that are specifically relevant.

In addition to searching through databases, this strategy also includes cross-referencing searches from bibliographies on relevant articles. This search helps ensure that all relevant research, including those that may not have appeared in the initial search, can be identified. Only articles published in the last 5 years are considered to maintain

the relevance of the findings to the current educational context. Inclusion criteria were used to filter the most relevant articles, namely: (1) articles that discuss the Problem-Based Learning model in the development of students' critical thinking skills and environmental concern, (2) research that evaluates the influence of PBL on critical thinking skills or environmental concern, (3) research conducted at the secondary or higher education level, and (4) articles published in indexed journals or reputable conference proceedings. Meanwhile, the article was excluded from the analysis when: (1) it did not provide quantitative or qualitative empirical data, (2) it was not explicitly relevant to the PBL theme, critical thinking skills, and environmental concerns, and (3) it was not available in English or Indonesian.

The selection process is carried out in stages to ensure the validity of the results. The first stage involves filtering by title and abstract. Articles deemed relevant are then reviewed in-depth on the full text to ensure compatibility with inclusion criteria. Each selected article is evaluated by several researchers to minimize bias in the selection. With this systematic model, the search strategy is designed to produce a representative, comprehensive, and relevant collection of literature. This model supports the integrity and validity of the data used in the meta-analysis and provides a strong foundation for evaluating the influence of the Problem-Based Learning Model on students' critical thinking skills and environmental concerns.

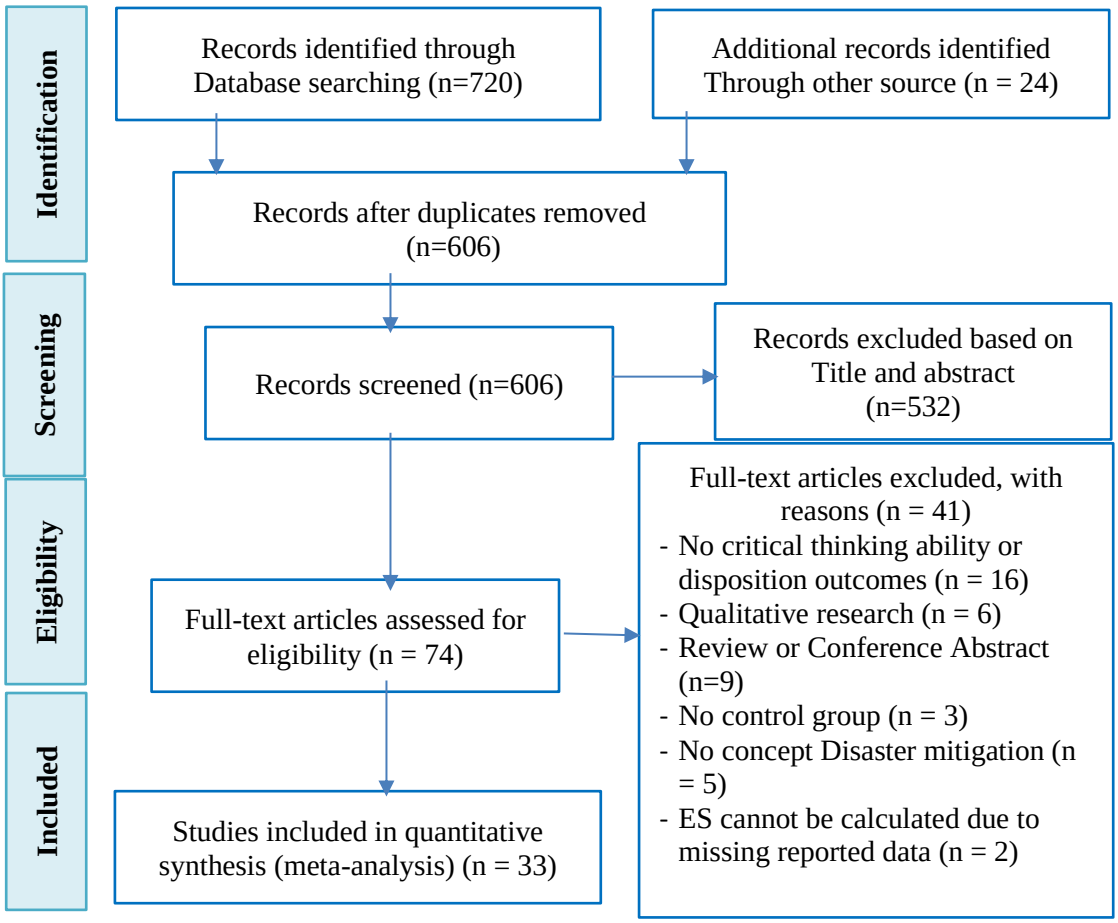

Figure.1 PRISMA flowchart of the study selection process

Meta-analysis was carried out by searching for articles using Google Scholar and collecting research data. The search for the article uses the keywords "Problem-Based Learning, Critical thinking skills and Environmental Concern". The articles are selected and selected for analysis, then assigned AF1, AF2 and so on to AF33. The data analysis carried out was using the effect size (ES) value with a group contrast model which included (1) estimating the value of ES, the amount of ES variance, and the standard error amount of ES; (2) making conclusions or interpreting the results of the analysis. Meta-analysis was used to determine the effect size of the use of the PBL model on science literacy ability by using the number of research subjects, average score of pretest, postest, and standard deviation. The formula used was the effect size according to Hedges's g in two independent groups. The calculation was carried out using Microsoft Excel to find the effect size (g). Cohen gives suggestions for interpreting d (which can also be used with g or Glass), where d = 0.20 is considered a small effect, d = 0.50 is considered a medium effect, and d = 0.80 is considered a large effect. For data analysis, 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

Inclusion and Exclusion Criteria

In this study, inclusion and exclusion criteria were applied to ensure that the articles included in the meta-analysis were of high quality and significant relevance to the topics discussed, namely the influence of the Problem-Based Learning Model on students' critical thinking skills and environmental concerns. Articles that meet the inclusion criteria must directly discuss the Problem-Based Learning Model and evaluate its impact on students' critical thinking skills and environmental concerns. Research conducted at the junior high school, high school and university levels will be included, because learning at this level is more relevant to develop critical thinking skills and environmental awareness. In addition, articles that use clear and verifiable methodologies, whether qualitatively, quantitatively, or mixed, and that report measurable empirical data, will be prioritized. Articles published in the last 5 years are selected to maintain relevance to current educational developments, and only articles published in English or Indonesian will be considered.

On the other hand, articles that meet one of the exclusion criteria will be excluded from this review. Articles that do not address relevant topics, such as those that do not relate the Problem-Based Learning Model to critical thinking skills or that do not evaluate its impact on students' environmental concerns, will be removed. In addition, articles that do not provide measurable empirical data, either quantitatively or qualitatively, or that do not report results relevant to the topic of this study will also be excluded. Articles that are reviews, opinions, or reports without strong empirical data, such as editorials or letters to

editors, will also not be included. Studies with weak methodological designs, such as those that are not clear in the implementation of experiments or that do not have adequate controls, will be excluded. Articles published before 2019, unless there is a compelling reason to include them based on the relevance of the findings, will also be excluded from this analysis. This study aims to ensure that only the most relevant and high-quality articles are used, so that the results of the meta-analysis obtained can provide valid and reliable findings regarding the influence of the Problem-Based Learning Model on students' critical thinking skills and environmental concerns.

Data Analysis

The data analysis in this study was carried out using quantitative and qualitative models to ensure that the findings produced were comprehensive and reliable. The analysis process begins with data extraction from the selected articles, which includes information related to the design of the Problem-Based Learning model and its impact on students' critical thinking skills and environmental concern (Sailer & Homner, 2020). Quantitatively, the data obtained from the results reported in the selected study will be analyzed using effect sizes to assess the influence of PBL on students' critical thinking skills and environmental concerns. The size of the effect was calculated based on the mean difference between the experimental and control groups, as well as the variability in the data (Kecinski, Messer, McFadden, & Malone, 2020).

Calculations will be made using relevant statistical software, such as Comprehensive Meta-Analysis (CMA) or R, which allows calculations of different measures of effect, such as Cohen's d, which can provide an idea of the magnitude of the impact of the intervention. In addition, a heterogeneity analysis will be conducted to evaluate the extent to which different research results have significant variability, which can be influenced by factors such as study design, context, or moderation variables. Qualitatively, the analysis was carried out by identifying the patterns that emerged from the learning design and the models used in each of the studies included in this review. The focus of this qualitative analysis is to understand how the Problem-Based Learning model is applied in the context of developing critical thinking skills and environmental care, as well as the factors that support or hinder the improvement of these two skills.

Qualitative data obtained from relevant articles will be analyzed using a narrative synthesis model to identify common findings related to learning strategies, methodologies used, and specific aspects of Problem-Based Learning that contribute to the achievement of desired outcomes (Filieri, Javornik, Hang, & Niceta, 2021). During the data analysis process, triangulation is used to verify the accuracy of the findings, by comparing the results of quantitative and qualitative analysis. In addition, the reliability of the analysis is maintained by ensuring that the data extraction and analysis process is carried out by more than one researcher, and any disagreements that arise during this process are resolved through discussion and consensus (Zheng et al., 2020). This process helps reduce bias in data interpretation and ensures that the final results obtained reflect a more holistic understanding of the influence of the Problem-Based Learning model on students' critical thinking skills and environmental concerns.

▪ RESULT AND DISSCUSSION

The results of data extraction identified the characteristics of 33 articles based on education level, research methods, and main findings summarized in Table 2. These

studies used a quantitative model to evaluate the influence of the Problem-Based Learning model on students' critical thinking skills and environmental concerns. Of the 33 studies, 13 of them used experimental quantitative methods, which provided a detailed explanation of the application and impact of PBL in developing both skills. The process of thematic analysis reveals two main themes. The first theme is the application of Problem-Based Learning as a problem-based learning model to improve students' critical thinking skills and environmental concerns. The second theme is the significant impact of PBL on the development of these two skills, which is supported by consistent research results. In addition, a literature review shows that Problem-Based Learning plays an important role in integrating critical learning and environmental awareness as part of the educational process, which is a key finding in most of the analyzed articles.

Table.2 Summary of research data, pretest, postest, effect size and error standard

Study ID	Data Code	Pretest	Postest	ICE	ONE
Yuliasandra *et al.*, 2023	AF1	56.0	78.0	0.78	0.045
Amin *et al.*, 2020	AF2	66.0	73.0	0.88	0.048
Umami *et al.*, 2023	AF3	68.6	78.4	0.80	0.043
Mustikasari *et al.*, 2021	AF4	64.6	82.1	0.82	0.042
Anggiani., 2022	AF5	65.3	80.7	0.87	0.050
Afana *et al.*, 2023	AF6	70.7	80.1	0.78	0.050
Hillary *et al.*, 2023	AF7	69.1	76.8	0.66	0.049
Yusuf., 2022	AF8	65.0	78.2	0.75	0.054
Jupriyanto *et al.*, 2023	AF9	68.4	78.0	0.76	0.053
Maharani *et al.*, 2024	AF10	63.9	84.1	0.83	0.044
Amin *et al.*, 2023	AF11	75.2	84.4	0.84	0.046
Adalta *et al.*, 2020	AF12	78.5	85.7	0.77	0.049
Meitiyani *et al.*, 2022	AF13	62.5	70.8	0.83	0.048
Ardiansyah *et al.*, 2024	AF14	61.0	71.0	0.84	0.050
Chusni *et al.*, 2021	AF15	72.1	80.3	0.80	0.051
Maulina *et al.*, 2024	AF16	75.8	83.1	0.80	0.053
Awaliyah *et al.*, 2023	AF17	50.5	81.8	0.84	0.052
Siregar *et al.*, 2024	AF18	75.0	85.0	0.79	0.053
Suhirman *et al.*, 2022	AF19	66.5	87.5	0.88	0.064
Hamdan., 2023	AF20	58.0	70.0	0.72	0.051
Ritongai *et al.*, 2021	AF21	64.4	86.8	0.81	0.050
Marnita *et al.*, 2021	AF22	71.5	84.3	0.88	0.061
Maulina *et al.*, 2023	AF23	73.0	86.7	0.83	0.056
Ernawati *et al.*, 2023	AF24	70.2	84.0	0.87	0.055
Rachman, *et al.*, 2020	AF25	64.6	78.7	0.80	0.050
Wibowo *et al.*, 2024	AF26	72.2	86.8	0.88	0.051
Ural *et al.*, 2020	AF27	61.7	76.8	0.89	0.060
Orhan *et al.*, 2022	AF28	74.2	88.8	0.82	0.051
Suhirman *et al.*, 2020	AF29	72.0	86.0	0.78	0.054
Ramdani *et al.*, 2021	AF30	68.0	82.0	0.81	0.060
Adhelacahya *et al.*, 2023	AF31	66.0	88.0	0.79	0.053
Jariah *et al.*, 2022	AF32	67.6	80.5	0.86	0.052
Wenno *et al.*, 2021	AF33	56.0	74.0	0.84	0.055

Based on the data in Table 2, this study showed a consistent improvement in pretest and posttest scores across all analyzed studies, with an average pretest score of 67.09 and a posttest score of 80.98. The calculated size effect ranged from 0.66 to 0.89, which showed a large to very large impact of the application of Problem-Based Learning on students' critical thinking skills and environmental concerns. Studies with the highest ES, as reported by Ural et al. (2020) with a score of 0.89, show that the application of PBL can have a significant influence on improving learning outcomes. In contrast, the study with the lowest ES, namely Hillary et al. (2023) with a score of 0.66, still shows a strong influence, although lower than other studies. A low standard of error in each study indicates reliable results and high consistency in findings. This data reinforces the evidence that PBL is an effective model for improving critical thinking skills and environmental awareness at various levels of education.

Table.3 Descriptive statistics

	Pretest	**Postest**
Valid	33	33
Missing	8	8
Mode	56.000	76.800
Median	67.600	81.800
Mean	67.094	80.982
Std. Deviation	6.319	5.232
IQR	7.600	7.000
Variance	39.926	27.378
Skewness	-0.573	-0.546
Std. Error of Skewness	0.409	0.409
Curtosis	0.318	-0.500
Std. Error of Kurtosis	0.798	0.798
Shapiro-Wilk	0.973	0.948
P-value of Shapiro-Wilk	0.560	0.113
Range	28.000	18.800
Minimum	50.500	70.000
Maximum	78.500	88.800
25th percentile	64.400	78.000
50th percentile	67.600	81.800
75th percentile	72.000	85.000
Sum	2214.100	2672.400

a The mode is computed assuming that variables are discreet.

Table 3 of Descriptive Statistics shows a significant increase in scores from pretest to posttest, with an average score of 67.09 for the pretest and 80.98 for the posttest. The lower standard deviation in the posttest (5.23) compared to the pretest (6.32) indicates a more homogeneous distribution of scores after the Problem-Based Learning (PBL) intervention. The median and quartile scores showed that most of the data were concentrated above the average score, with a narrower interquartile range on the posttest (7.0) than on the pretest (7.6), confirming that student learning outcomes were more

evenly distributed after the implementation of PBL. Negative skewness on both measurements (pretest -0.573 and posttest -0.546) indicates that most students score above the median grade. This increase reflects the effectiveness of PBL in encouraging the improvement of students' critical thinking skills and environmental concern (Syamsinar et al., 2023).

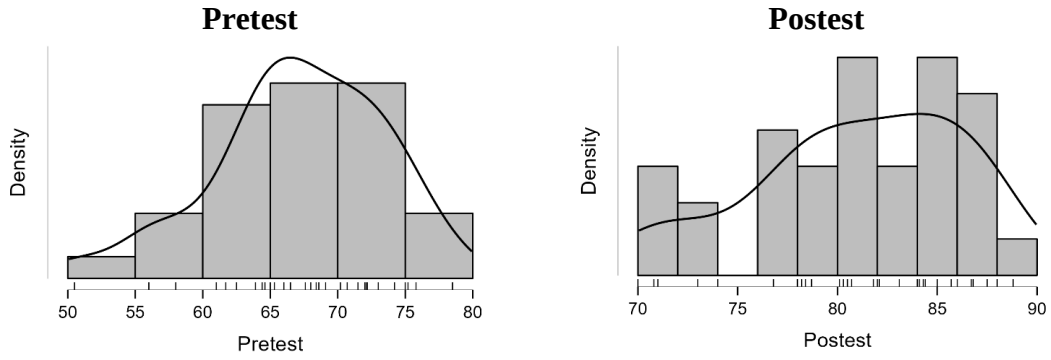

Figure 2. Distribution plots

Figure 2 Distribution Plots shows significant changes in the distribution of pretest and posttest scores after the Problem-Based Learning intervention. On the pretest graph, the distribution of scores appears to be more dispersed, reflecting greater variation among students before the implementation of PBL. In contrast, the distribution of posttest scores showed a more centralized pattern with higher distribution peaks, signaling an improvement in overall learning outcomes. This change was supported by a shift in higher mean and median scores on the posttest, as noted in the descriptive analysis. A more centralized distribution pattern on the posttest also indicates that the PBL model has managed to have a consistent impact on most students, with improved critical thinking skills and environmental awareness evenly distributed at various levels of early performance.

Table.4 Fixed and random effects

	Q	**Df**	**p**
Omnibus test of Model Coefficients	8414.784	1	<.001
Test of Residual Heterogeneity	30.594	32	0.538

Note. p -values are approximate.

Note. The model was estimated using Restricted ML method.

Table 4 Fixed and Random Effects illustrates the analysis of the impact of the application of Problem-Based Learning on the development of students' critical thinking skills and environmental concern. The omnibus test of model coefficients produced a Q value of 8414.784 with degrees of freedom (df) of 1 and $p < 0.001$. These results are statistically significant and show that the model used in this analysis is overall able to explain the variation in data well. In addition, the residual heterogeneity test yielded a Q value of 30.594 with a df of 32 and $p = 0.538$, which showed that there was no significant heterogeneity among the analyzed studies. The low heterogeneity indicates that the observed effects are quite uniform across the various contexts of the included studies.

However, it is important to note that the low heterogeneity in this analysis was not accompanied by further exploration of the moderating factors.

Moderator analysis is a necessary approach to identify contextual variables that can affect outcomes, such as the level of education of students, the duration of PBL implementation, the complexity of the problem used, or the involvement of educators. These factors have the potential to be important determinants of PBL success, but have not been analyzed in depth in this study. The absence of moderator analysis limits insights into how the specific characteristics of PBL implementation affect learning outcomes under various conditions. Thus, further research that incorporates moderator analysis can provide a more detailed understanding of specific contexts in which PBL is more effective. In addition, the analysis can enrich practical recommendations for the implementation of PBL that are more targeted and relevant at various levels of education or socio-cultural conditions.

Table.5 Coefficients

	Estimate	**Standard Error**	**z**	**p**
intercept	0.813	0.009	91.732	<.001

Note. Wald test.

Table 5 Coefficients shows the estimated influence of the Problem-Based Learning Model on students' critical thinking skills and environmental concerns. The estimated coefficient of 0.813 with a standard error of 0.009 shows that PBL has a large and statistically significant effect on learning outcomes, as evidenced by a z-value of 91.732 and a p < of 0.001. This very significant value indicates that the consistent application of PBL has a positive impact on the development of both skills. The high coefficient also reflects the effectiveness of PBL in improving learning outcomes, supporting findings from previous analyses that showed an increase in mean posttest scores compared to pretest in the various studies analyzed.

Table.6 Fit measures

	REML
Log-Likelihood	50.283
Deviance	-100.567
AIC	-96.567
BIC	-93.635
Aicc	-96.153

Table 6 Fit Measures shows the model fit indicators used in the meta-analysis. The log-likelihood value of 50.283 and the deviation of -100.567 show that the model is able to explain the data well. Other indicators, such as AIC (-96,567), BIC (-93,635), and AICc (-96,153), all of which have negative values, indicate an efficient model in accommodating data complexity without overfitting. These values show that the model applied has a good fit and high validity in estimating the influence of Problem-Based Learning on students' critical thinking skills and environmental concerns. These results reinforce the belief that the statistical model used is appropriate to support the interpretation and conclusions of this study.

Table.7 File drawer analysis

	Fail-safe N	Target Significance	Observed Significance
Rosenthal	101929.000	0.050	<.001

Table 7 of the File Drawer Analysis shows the results of tests to evaluate potential publication biases that may not have been detected in this meta-analysis. The Fail-safe N value of 101.929 indicates that even if a large number of studies with negative results are included in the analysis, the main findings of the study remain significant ($p < 0.001$). In other words, while there is a possibility of unpublished studies, the large number is not enough to reverse the conclusion that Problem-Based Learning has a significant positive impact on students' critical thinking skills and environmental concerns. These results show that the findings of this meta-analysis are quite robust and are not affected by publication bias.

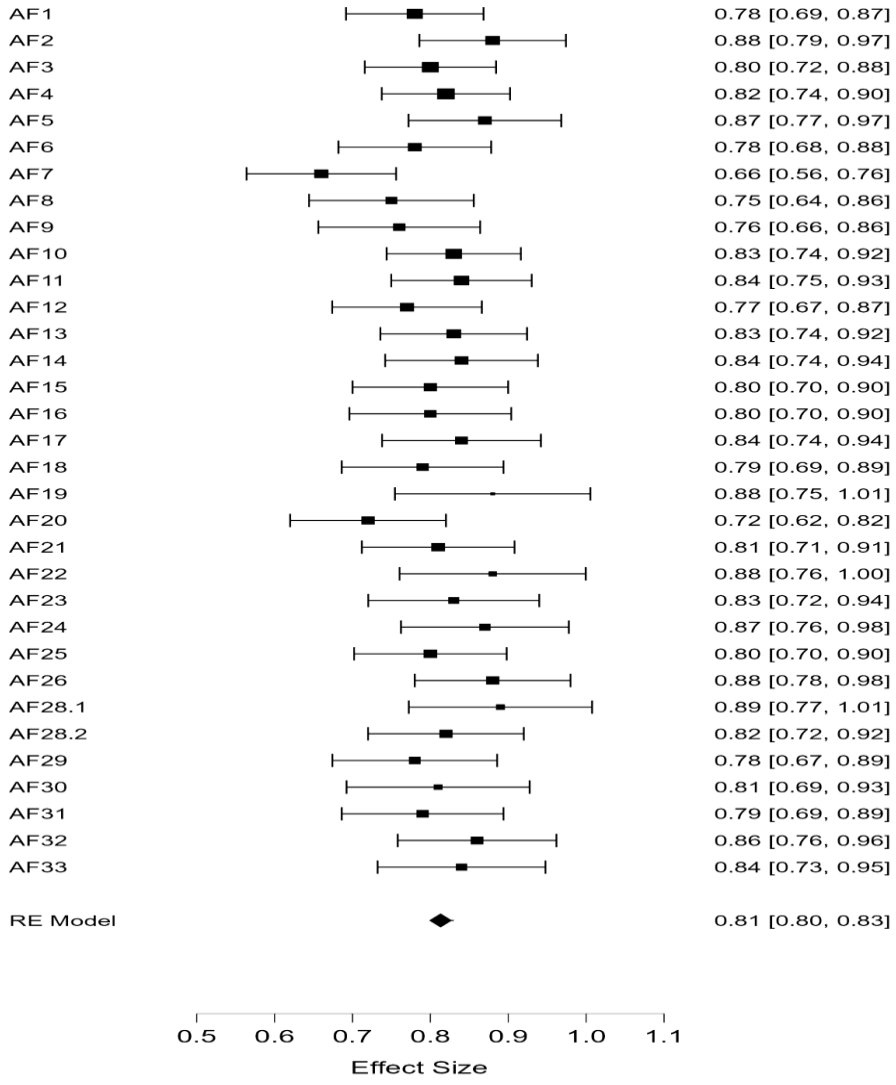

Figure 3. Forest plot

Figure 3 Forest Plot shows the effect size distribution of the studies analyzed in this meta-analysis, which illustrates the impact of the application of Problem-Based Learning on students' critical thinking skills and environmental concerns. In this plot, each horizontal line represents the confidence interval for the effect size of each study, while the box in the middle of the line shows the estimated effect size. The box area describes the relative weight of each study in the analysis, with greater weight given to studies that have smaller variants or larger sample sizes. Most of the boxes are on the positive side, indicating that the majority of studies support the positive effects of PBL implementation (Johansson, 2020). Almost all confidence intervals do not cover zero, which indicates that the impact of PBL is statistically significant in improving students' critical thinking skills and environmental concern. These results also reflect the consistency of effect measures across different studies. Studies with the largest effect size, such as those reported by Ural et al. (2020) with a value of 0.89, showed a very significant impact, while studies with lower effects, such as Hillary et al. (2023) with a value of 0.66, still showed a positive impact. The uniform length of the confidence interval indicates low heterogeneity, which is consistent with the results of the heterogeneity test in Table 4. This Forest Plot corroborates the finding that the application of PBL is an effective learning approach in various educational contexts, both secondary and higher education levels (Phelan et al., 2022). However, while these results show consistency, it is important to note that this analysis has not yet explored moderating factors such as the duration of implementation, problem complexity, or students' social backgrounds, which may affect the effectiveness of PBL (Ngoc Le, 2023). Thus, although the Forest Plot results provide strong evidence of the effectiveness of PBL, further research with moderator analysis can provide more detailed insights to improve the implementation of PBL in various educational settings.

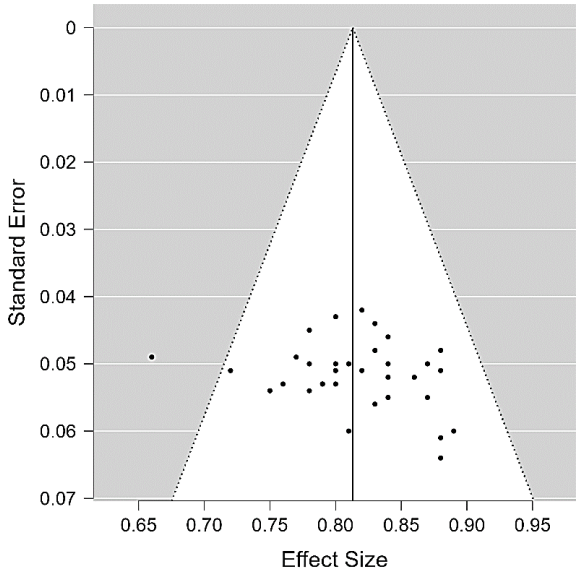

Figure 4. Funnel plot

Figure 4 Funnel Plot provides an overview of the effect size distribution of the various studies analyzed in this meta-analysis, which aims to detect the possibility of publication bias. In this plot, each point represents a single study, with the horizontal position indicating the size of the effect and the vertical position indicating the precision

(usually measured by standard error). Ideally, these dots would be symmetrically spread around a vertical line that represents the average effect of the entire study, forming a funnel-like pattern. In Figure 4, most of the points are symmetrically distributed around the midline, suggesting that the majority of studies have an effect size consistent with the mean effect of the meta-analysis. This symmetry indicates that significant publication bias was not detected in this meta-analysis. In addition, the dots located at the top of the funnel represent studies with large sample sizes and high levels of precision, while the dots at the bottom of the funnel represent studies with small sample sizes or larger standard errors.

Although the distribution of data at the bottom of the funnel appears to be more scattered, the overall pattern remains symmetrical, which supports the finding that the results of this meta-analysis are free of selection bias against studies with specific results. This balanced distribution strengthens the reliability of the meta-analysis results and provides evidence that the application of Problem-Based Learning has a significant positive impact on students' critical thinking skills and environmental concern. However, while these Funnel Plot results are promising, it's important to consider that this tool has limitations. Symmetrical distribution on the plot does not fully guarantee the absence of other biases, such as selection biases that are not associated with statistically significant outcomes (Zheng et al., 2020). Therefore, additional analyses, such as Trim-and-Fill or Fail-Safe N, are needed to corroborate the validity of the findings. Thus, Figure 4 of the Funnel Plot provides visual evidence to support that the findings of this meta-analysis are reliable and not affected by publication bias, so that the results regarding the impact of PBL on students' critical thinking skills and environmental concern can be used to support strong scientific recommendations.

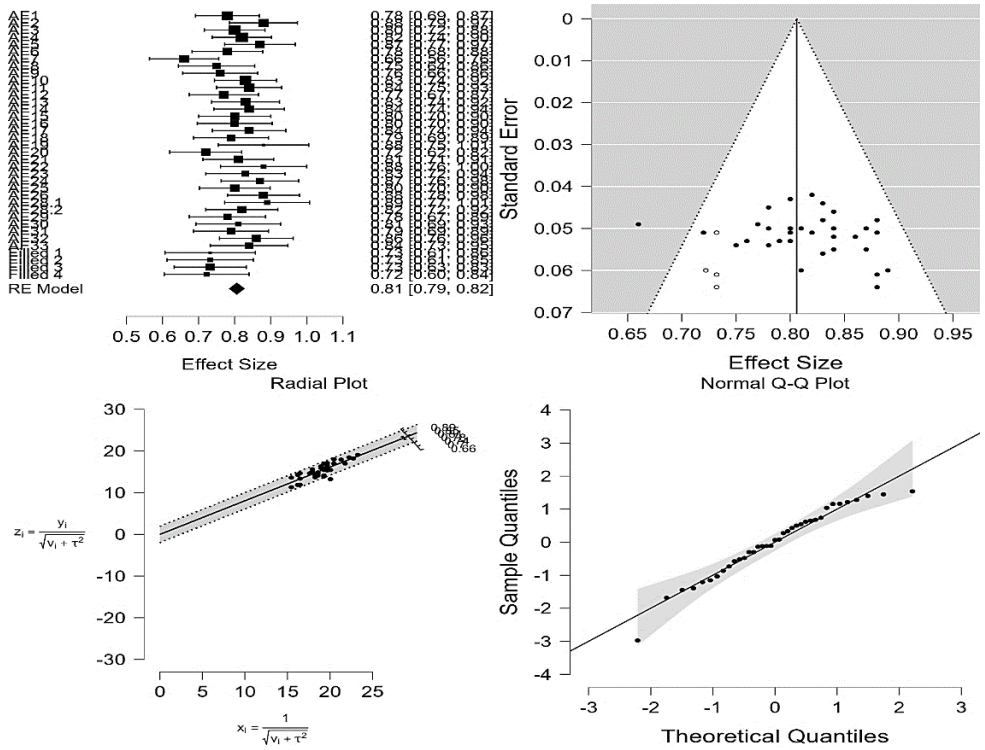

Figure 5. Trim-Fill Analysis

Figure 5 Trim-Fill Analysis shows the results of the analysis aimed at detecting and correcting potential publication bias in this meta-analysis. The Trim-Fill method works by "trimming" studies that are considered distorted due to publication bias and "filling" the distribution with hypothetical studies to produce a more balanced picture. The results of the analysis in Figure 5 show that the distribution of the effect size after the trim and fill process does not change significantly compared to the initial distribution. The addition of hypothetical study points did not affect the mean effect or the confidence interval, which still did not include zero. This indicates that the consistent application of Problem-Based Learning has a significant positive impact on students' critical thinking skills and environmental concerns, even after considering the possibility of publication bias (Rodriguez-Morales et al., 2020).

While these results indicate the reliability of the findings, it is important to consider a range of contextual factors that can affect the effectiveness of PBL in the studies analyzed. First, the design and complexity of the problem used play an important role. Relevant, contextual, and challenging enough problems can increase student engagement as well as facilitate the development of critical thinking skills (Monteiro, Sherbino, Sibbald, & Norman, 2020). Second, the duration of PBL implementation is also an important factor. Programs with too short a duration may not provide enough time for students to fully internalize the critical thinking process. Third, education level also affects outcomes, where students at the higher education level tend to benefit more than students at the secondary level, given their capacity to process more complex information (This, Attribution-noncommercial-noderivs, By-nc-nd, If, & Rose, 2020). In addition, social and cultural contexts also play a significant role. In an environment that encourages collaboration, PBL tends to be more effective than in more individualistic cultural contexts (Vasquez & Lara, 2020). The role of educators cannot be ignored either; educators who are skilled in facilitating PBL, encouraging reflective discussions, and providing relevant guidance can significantly improve the effectiveness of the implementation of these methods (Chernikova et al., 2020). Thus, although Figure 5 of the Trim-Fill Analysis shows convincing results regarding the validity of the findings of this meta-analysis, future research needs to further explore these contextual factors to optimize the application of PBL in various educational conditions.

▪ CONCLUSION

This meta-analysis research shows that the Problem-Based Learning (PBL) Model has a significant impact on improving students' critical thinking skills and environmental awareness. With an average pretest score of 67.09 which increased to 80.98 on the posttest, as well as a size effect (ES) ranging from 0.66 to 0.89, this study consistently shows that PBL exerts a large to very large influence. A more homogeneous distribution of scores on the posttest (standard deviation decreased from 6.32 to 5.23) also indicated an even improvement among students after the intervention. The effectiveness of PBL is supported by the model's ability to integrate relevant real-world problem-based learning, thereby improving students' analytical abilities while fostering their awareness of global environmental issues. Thus, based on the analysis of 33 articles, it is shown that the implementation of PBL provides consistent results at various levels of education, both secondary and tertiary. The study with the highest size effect, with a value of 0.89, showed a very significant impact, while the low standard of error across all studies (mean SE ≈

0.05) underscored the reliability of the results obtained. This research also highlights the importance of supporting factors such as learning design, interaction between students and teachers, and socio-cultural context in maximizing the effectiveness of PBL. Thus, it can be concluded that the Problem-Based Learning model has a strong influence in improving students' critical thinking skills and environmental concerns.

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