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Meta-Analysis: The Effect of PBL Learning Model on High School Students' Mathematical Critical Thinking Skills

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Abstract. *In Indonesia, mathematical critical thinking is a skill that students often lack and therefore needs attention. This study aims to analyze the effectiveness of implementing the PBL model on students' mathematical critical thinking skills at the senior high school level, overall and by study characteristics such as sample size, region, and year of study, using a meta-analysis. A total of 13 primary studies that met the criteria were analyzed using a random-effects model in Comprehensive Meta-Analysis software. The results show that the combined effect size obtained is 1.011, which falls into the very large effect category, indicating that the PBL model has a positive and significant effect compared to conventional learning. In the analysis of study characteristics by effect size category, the group that conducted learning online during the COVID-19 pandemic had an effect size in the moderate category. In contrast, all other groups produced effect sizes in the very large category. Meanwhile, the heterogeneity test showed no significant differences in effect sizes across groups for the three study characteristics. These findings confirm that the PBL model is effective in improving students' mathematical critical thinking skills at the senior high school level, but tends to be less effective when learning is conducted online. The implications of this study provide recommendations for teachers to optimize the implementation of PBL in the mathematics learning process and to consider its use across various situations and conditions.*

Keywords: *Mathematical Critical Thinking Skills, Problem-Based Learning, High School Students, Meta-Analysis.*

INTRODUCTION

Mathematics is a subject that requires students to think critically when solving problems (Suciati et al., 2022); therefore, critical thinking skills in mathematics are abilities that every student must possess and master. This is in accordance with the opinion of Indriani et al., (2022), who state that critical thinking skills are among the important abilities that students must master.

However, in reality, students in Indonesia lack mastery of critical thinking skills, particularly in mathematics. This is indicated by students' mathematical critical thinking skills, which are still classified as low (Awaluddin et al., 2024; Putri et al., 2022; Taha et al., 2022). Therefore, students' critical thinking skills in mathematics need improvement.

Improving students' mathematical critical thinking skills can be achieved by implementing an appropriate learning model. According to Indriani et al., (2022), such a learning model comprises several processes, namely mastery of the material, internalization, and transfer of the material to different cases; therefore, a suitable learning model is problem-based learning (PBL). This aligns with one of the objectives of the PBL model, which is to develop students' critical thinking skills in problem-solving (Nurrohma & Adistana, 2021).

Various studies have examined the effect of the PBL model on students' mathematical critical thinking skills. However, these studies have produced varied results. Hidayat et al., (2024), Kasmita & Khalsum (2025), and Wida et al. (2025) found that the PBL model has a positive and significant effect on improving students' mathematical critical thinking skills. However, Olivia (2025) and Olivia & Fitri (2025) found different results. There is no difference in mathematical critical thinking skills between students taught using the PBL model and those taught using conventional learning.

The differences in these research findings may lead to subjective conclusions; therefore, a study that can provide an accurate conclusion is needed, namely one that uses a meta-analysis research method. Meta-analysis can produce an accurate conclusion by quantitatively summarizing a collection of primary studies conducted by previous researchers using an effect size measure (Retnawati et al., 2018).

Meta-analytic studies on the effect of the PBL model on students' mathematical critical thinking skills in general have been conducted by Rohmah et al. (2022) and Suparman et al. (2021), with effect sizes of 1.47 and 1.109, respectively, which are classified as high effects. Both studies included education level as a moderator, yielding effect sizes for each educational level. However, the obtained effect sizes were derived from only a small number of primary studies; for example, at the elementary school level, an effect size of 1.74 was obtained based on only one primary study. Therefore, a study focusing on a single level of education is needed to yield specific research results from a larger number of primary studies.

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Studies that specifically focus on elementary school students have been conducted by Mahmudah (2020), with an effect size of 1.82 based on 10 primary studies, while studies that specifically focus on junior high school students have also been conducted by Yohannes et al. (2021), which obtained an effect size of 0.970 based on 15 primary studies. However, studies specifically focusing on senior high school students have not yet been conducted; therefore, this meta-analysis focuses specifically on senior high school students in Indonesia.

This study examines the effect of the PBL model on the mathematical critical thinking skills of senior high school students overall and, specifically, the differences in the magnitude of the effects across primary studies based on moderator variables such as sample size, region, and year of study. The results of this study are important because they provide a comprehensive overview of the PBL model's effectiveness in improving high school students' mathematical critical thinking skills, while also revealing the factors that can influence the magnitude of this effect. Therefore, educators can consider using the PBL model in line with existing conditions and circumstances, such as the number of students in the class, the school's location, and the policies in effect in a particular academic year, to improve students' mathematical critical thinking skills.

RESEARCH METHOD

The method used in this study is meta-analysis, which synthesizes primary studies on the effect of the PBL model on the mathematical critical thinking skills of senior high school students. In its implementation, this study follows the stages of meta-analysis described by Borenstein et al. (2009), namely: (1) determining inclusion criteria, (2) procedures for data collection and extraction, and (3) statistical techniques used. The flow of the meta-analysis stages is shown in Figure 1.

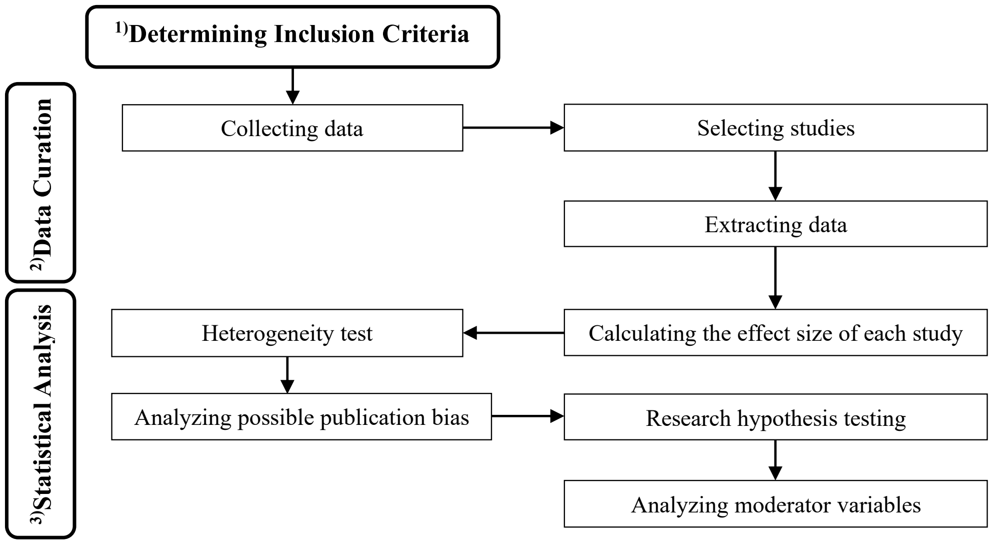

Figure 1. Meta-Analysis Stage Flow

Inclusion Criteria

The inclusion criteria in this study use the PICOS format (Participants, Interventions, Comparators, Outcomes, and Study Design) (Liberati et al., 2009).

1. Participants: Studies whose participants are senior high school students in Indonesia.
2. Interventions: Studies that implement the PBL learning model in the experimental class.
3. Comparator: Studies that implement conventional models in the control class.
4. Outcomes: Studies targeting the achievement of students' mathematical critical thinking skills.
5. Study Design: Studies that use experimental or quasi-experimental designs.

Data Curation

A total of 115 research articles were collected from electronic databases, namely Google Scholar, Semantic Scholar, Publish or Perish, and GARUDA, using the keywords' problem-based learning' and 'mathematical critical thinking skills'. In addition, 1 research data point, a study from the gray literature (specifically a thesis), was obtained, bringing the total to 116 studies.

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These studies were then included in the selection process, in which the inclusion criteria were applied. The study selection in this research followed PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), which comprises four stages: identification, screening, eligibility assessment, and study inclusion (Liberati et al., 2009). After going through these stages, only 13 studies met the criteria and were selected. The study selection process is summarized in the PRISMA flow diagram in Figure 2.

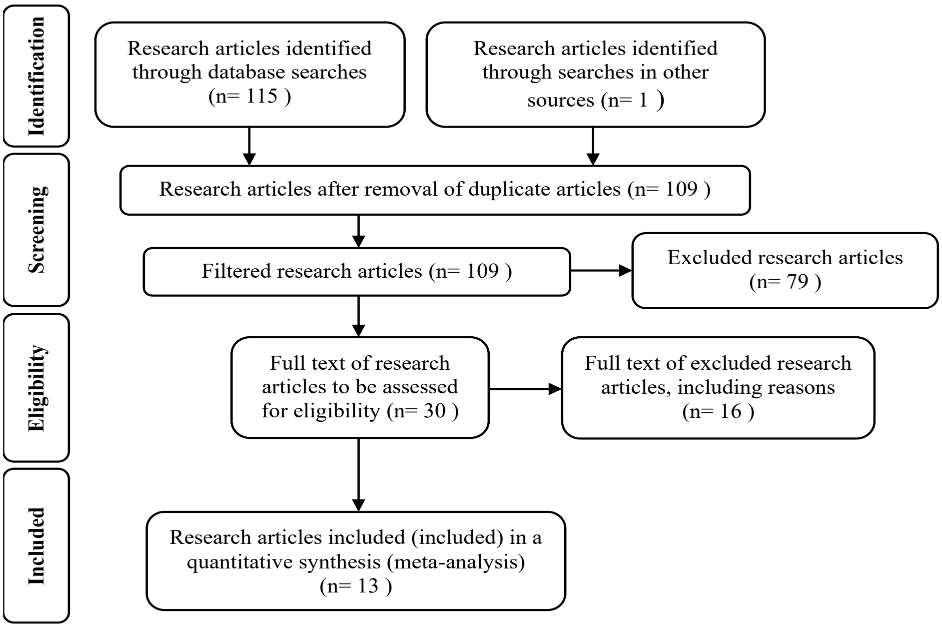

Figure 2. PRISMA Flow Diagram (Moher et al., 2009).

Furthermore, the 13 studies were extracted using a meta-analysis instrument in the form of a coding sheet. The coding was carried out according to the guidelines provided in the protocol sheet, which two expert validators had validated. The coding process involved two experienced coders to ensure the validity of the extracted data. To further ensure this, a reliability test was conducted to measure the consistency of the two coders in the data extraction process.

Statistical Analysis

In this meta-analysis, the effect size represents the magnitude of the PBL model's effect on the mathematical critical thinking skills of senior high school

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students. The statistical analysis procedures used in this study refer to Borenstein et al. (2009), namely: (1) calculating the effect size of each primary study, (2) conducting a heterogeneity test and determining the estimation model used, (3) analyzing the possibility of publication bias, and (4) conducting hypothesis testing. All of these statistical analyses were carried out with the assistance of Comprehensive Meta-Analysis (CMA) version 4.0.

The formula used to calculate the effect size in this study is Hedges' g formula, because unlike Cohen's d formula, which tends to produce bias in studies with small sample sizes, Hedges' g does not produce such bias. The interpretation of the effect sizes in this study uses Cohen's classification, as shown in Table 1 (Ruli & Indarini, 2022).

Table 1. Effect Size Categories

Effect Size (ES)	Category
$0 < ES \leq 0,2$	Small effect
$0,2 < ES \leq 0,5$	Moderate effect
$0,5 < ES \leq 0,8$	Large effect
$0,8 < ES$	Very large effect

The heterogeneity test was conducted by examining the null hypothesis that the effect sizes across primary studies are homogeneous, using the Q statistic and observing the p-value. If $p < 0.05$, the null hypothesis is rejected, and the random-effect model is used to estimate the overall effect size. Conversely, if $p > 0.05$, the null hypothesis is accepted, and the fixed-effect model is used. The analysis related to the causes of differences in the magnitude of the effect, in this case differences in effect size values, was carried out by investigating the predetermined moderator variables, namely sample size, region, and year of study. This analysis can be conducted if the estimation model is a random-effects model.

The possibility of publication bias can be detected and corrected using several methods, including funnel plots, trim and fill, and Rosenthal's fail-safe N (FSN) statistic. The distribution of effect sizes in each primary study, when not symmetrical around the vertical line in a funnel plot, suggests the possibility of publication bias. Trim and fill is used to estimate the number of missing studies and to address this by removing the most extreme small studies. In contrast, Rosenthal's

FSN statistic is used to ensure that the study is robust and resistant to existing publication bias (Borenstein et al., 2009). A meta-analysis study is considered resistant to publication bias if the result of FSN / (5k + 10) > 1, where k represents the number of studies analyzed (Mullen et al., 2001).

Hypothesis testing in this study was conducted by examining the null hypothesis that there is no significant effect of the PBL model on the mathematical critical thinking skills of senior high school students, using the Z statistic and observing the p-value. If $p < 0.05$, the null hypothesis is rejected, and it can be concluded that the PBL model has a significant effect on the mathematical critical thinking skills of senior high school students. Conversely, if $p > 0.05$ is obtained, then the null hypothesis is accepted.

RESULT AND DISCUSSION

Based on the established systematic review protocol, a total of 13 primary studies were identified and selected, all of which met the pre-specified inclusion criteria and successfully passed a rigorous quality assessment stage. To mitigate subjectivity and ensure data integrity, the extraction process was conducted collaboratively by two independent coders, the results of which were subsequently mapped in detail within Table 2. A significant methodological note regarding this presentation is that, although there were 13 distinct documents, Table 2 displayed 15 units of analysis; this occurred because two primary studies explored two independent comparisons, necessitating that each unit be treated as a separate data entity for analytical precision. The entirety of the extracted data served as the primary input for the meta-analysis procedure, which was structured into four fundamental phases: it commenced with the quantification of effect sizes for each study to standardize findings, followed by a comprehensive heterogeneity test to determine the most representative estimation model (fixed or random effects) regarding data variance. Furthermore, analyses were performed to detect potential publication bias through specific statistical procedures to guarantee the credibility of the outcomes, which ultimately culminated in hypothesis testing to confirm the overall significance of the research findings.

Table 2. Data Extraction Results

Code	Citation	Statistical Data						
		PBL			Conventional			t-value
		n	$\overline{x}$	s	n	$\overline{x}$	s	
M01	Arifin et al., 2020a	48	79.58	4.98	59	72.66	5.76	
M02	Arifin et al., 2020b	49	84.97	5.69	43	82.71	5.74	
M03	Awami et al., 2022	32	72.03	8.09	31	68.74	7.83	
M04	Fedi et al., 2019	24	78.89	8.84	26	66.07	8.56	
M05	Hidayat et al., 2024	36	80.14	12.28	35	66	13.76	
M06	Kasmita & Khalsum, 2025	30	88	6.34	30	78.87	5.89	
M07	Olivia, 2025	35	13.09	1.36	35	12.71	1.32	
M08	Sarwoedi et al., 2021a	28	73.32	5.54	27	78.19	6.34	
M09	Sarwoedi et al., 2021b	28	73.54	8.45	28	71.25	7.77	
M10	Utami et al., 2017	25	78.88	9.48	26	60.32	8.43	
M11	Wida et al., 2025	30	86.53	3.65	30	81.66	3.8	
M12	Zalukhu et al., 2024	31	74.22	11.28	31	56.67	8.79	
M13	Zulkarnain et al., 2016	33	12.61	3.43	33	8.7	2.87	
M14	Simbolon & Surya, 2023	31			31			3.554
M15	Wahyu et al., 2017	34			36			10.229

The first stage of the statistical analysis was calculating the effect size for each primary study. Based on the data presented in Table 2 above, the effect sizes for each primary study were calculated and are presented in Table 3.

Table 3. Effect Size Results of Each Primary Study

No	Author	Effect Size	Standard Error	Lower Limit	Upper Limit
1	Arifin et al., 2020a	1.267	0.212	0.852	1.681
2	Arifin et al., 2020b	0.392	0.209	-0.018	0.802
3	Awami et al., 2022	0.408	0.252	-0.085	0.901
4	Fedi et al., 2019	1.451	0.314	0.835	2.067
5	Hidayat et al., 2024	1.073	0.251	0.580	1.566
6	Kasmita & Khalsum, 2025	1.473	0.288	0.908	2.037
7	Olivia, 2025	0.274	0.238	-0.191	0.740
8	Sarwoedi et al., 2021a	-0.807	0.277	-1.350	-0.265
9	Sarwoedi et al., 2021b	0.278	0.265	-0.241	0.797
10	Utami et al., 2017	2.040	0.342	1.370	2.710
11	Wida et al., 2025	1.291	0.281	0.741	1.841
12	Zalukhu et al., 2024	1.714	0.294	1.137	2.291
13	Zulkarnain et al., 2016	1.222	0.266	0.701	1.742
14	Simbolon & Surya, 2023	0.891	0.263	0.375	1.407
15	Wahyu et al., 2017	2.419	0.313	1.806	3.032

At the 95% confidence level, Table 3 shows that the effect sizes across the primary studies range from -0.807 to 2.419. Based on the classification, out of the 15 effect size values, there are 0 studies with a small effect, 4 studies with a moderate effect, 0 studies with a large effect, 10 studies with a very large effect, and 1 study with a negative effect size value, which indicates that the PBL model is not more effective than the conventional learning model.

Next, the second stage was conducted: the heterogeneity test, followed by the determination of the estimation model used to calculate the overall effect size. In Table 4, the Q value obtained is 116.338 with a p-value of 0.000. This indicates that the distribution of effect sizes is heterogeneous at the $p < 0.05$ significance level, suggesting that effect sizes across studies vary. This variation is reflected in the I-squared value of 87.966, which means that approximately 87% of the variation in effect sizes is due to real heterogeneity rather than sampling error. Since the I-squared value is ≥75%, this study indicates a high level of heterogeneity (Mullen et al., 2001). Based on these results, the homogeneity hypothesis is rejected, and the random-effect model is therefore used for estimation.

Table 4. Comparison of Results Based on Estimation Models

No	Model	n	Z	p-value	Effect size	Standard error	95% CL		Q	P-value	I-squared
							Lower limit	Upper limit			
1	Fixed effect	15	13.618	0.000	0.927	0.068	0.794	1.061	116.338	0.000	87.966
2	Random effect	15	5.120	0.000	1.011	0.198	0.624	1.398			

Next, the third stage was conducted, namely the analysis of potential publication bias. Figure 3 shows the funnel plot in this study.

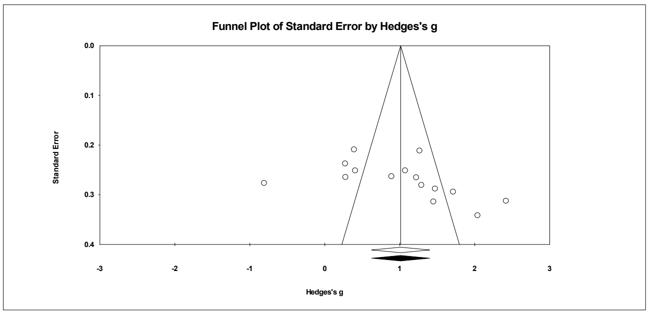

Figure 3. Funnel Plot of the Study

As shown in Figure 3, the distribution of effect sizes is not entirely symmetrical around the vertical line; therefore, the trim-and-fill test was conducted to detect and address publication bias. The results of this test are shown in Table 5.

Table 5. Results of the Trim and Fill Test Using the Random Effect Model

	Studies trimmed	Hedges'g	Lower limit	Upper limit	Q value
Observed value	0	1.01129	0.62414	1.39843	116.33753
Adjusted value		1.01129	0.62414	1.39843	116.33753

The test results show that no studies need to be removed or added to this research. This is evident in Table 5, which shows that Hedges' g does not differ before and after the trim-and-fill procedure. Furthermore, an examination of Rosenthal's FSN statistic was conducted. The calculation performed using CMA software shows an N value of 770. When calculated using the formula $770/(5\times15+10)$, the result is 9.06, which is greater than 1. This indicates that the primary studies analyzed in this research are robust to publication bias.

The fourth stage is conducting the hypothesis testing. It has been determined that the estimation model used in this study is a random-effects model. Based on this estimation model, Table 5 shows that the 95% confidence interval ranges from 0.624 to 1.398, indicating that the mean difference may occur anywhere within this range. The overall effect size of the primary studies in this research is 1.011, which is categorized as a very large effect. In addition, a Z value of 5.120 with a p-value of 0.000 was obtained, so that $p < 0.05$. This means the null hypothesis is rejected, and it can be concluded that implementing the PBL model has a positive and significant effect on the mathematical critical thinking skills of senior high school students compared to conventional models.

In addition to the four main stages, an additional stage was conducted, namely the analysis of moderator variables such as sample size, region, and year of study on the 15 effect sizes obtained from 13 primary studies by examining variations across the primary studies. Based on the data extraction results regarding the moderator variables, a summary was compiled in Table 6. The table also presents the calculation results used in this analysis.

Table 6. Results of Moderator Analysis: Data Extraction and Calculations

No	Moderator variables	Group	n	Hedge's g	Test of null (2-Tailed)		Heterogeneity		
					Z	P	Q	Df	p
1	Sample Size	<= 30	6	0.945	2.223	0.026	0.052	1	0.819
		>= 31	9	1.054	4.928	0.000			
2	Research Region	Sumatera	8	0.992	2.746	0.006	4.083	3	0.253
		Sulawesi	1	1.473	5.111	0.000			
		Jawa	5	0.878	4.251	0.000			
		Nusa Tenggara	1	1.451	4.619	0.000			
3	Year of Study	Before the COVID-19 pandemic	6	1.437	4.884	0.000	3.760	2	0.153
		During the COVID-19 pandemic	5	0.494	1.260	0.208			
		After the COVID-19 pandemic	4	1.013	3.681	0.000			

Sample Size

Studies with 1–30 participants have an effect size of 0.945, which, based on the classification, is categorized as a very large effect, similar to studies with 31 participants or more, which have an effect size of 1.054, also in the very large effect category. In addition, for the heterogeneity test between these two samples, the Q value is 0.052, with $p > 0.05$.

Research Region

By region, this study shows varying effect sizes. The effect sizes in Sulawesi and Nusa Tenggara are 1.473 and 1.451, respectively, which are very large compared to those in Sumatra and Java, at 0.992 and 0.878, respectively. However, all of these effect sizes fall into the same category, namely, very large effects. In the heterogeneity test, a Q value of 4.083 with $p > 0.05$ was obtained.

Year of Study

Based on the year of the study, the effect sizes obtained in the pre and post-COVID-19 pandemic groups were 1.437 and 1.013, respectively, which fall into the very large effect size category. Meanwhile, in the pandemic group, the effect size obtained was only 0.494, which is considered a moderate effect. Furthermore, the heterogeneity test yielded a Q value of 3.760 ($p>0.05$).

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The analysis in this study indicates that the PBL model has a significant positive effect on the mathematical critical thinking skills of senior high school students compared to conventional learning, with an overall effect size of 1.011, which falls into the very large effect category. This finding is very different from the effect size reported by Asror (2016) in his analysis at the senior high school level on the effect of PBL on students' mathematical skills, which was 0.24 and categorized as a small effect. In contrast, the study by Rohmah et al. (2022) on the effect of PBL on students' mathematical critical thinking skills supports this finding, with an effect size of 1.73 at the senior high school level. In addition, the study conducted by Yohannes et al. (2021), which also investigated the effect of PBL on students' mathematical critical thinking skills, reported an overall effect size of 0.970, which is categorized as a very large effect. Therefore, the use of the PBL model in schools, particularly at the senior high school level, is highly recommended to improve students' critical thinking skills in mathematics.

Based on sample size, referring to the effect size values of both groups, which fall into the same category, namely very large effects, the PBL model is highly suitable for improving the mathematical critical thinking skills of senior high school students, both in small and large samples. Given the p-value p 0.05 in the heterogeneity test, the effect size of implementing the PBL model on students' mathematical critical thinking skills does not differ between the two sample sizes. These two findings lead to the conclusion that PBL is very effective when applied in classrooms, regardless of the number of students. The results obtained differ from those of Tamur et al. (2020), which state that the effect size is greater with a sample size of 30 or fewer than with a sample size of 31 or more. However, a meta-analysis study with a similar topic, namely the effect of PBL on students' mathematical critical thinking skills, conducted by Yohannes et al. (2021), supports the findings of this study, indicating that there is no difference in the effect of the PBL model on senior high school students' critical thinking skills based on sample size.

Based on the research region, the effect sizes across the four groups are all very large. Based on the heterogeneity test results for these four groups, the p-value was $p > 0.05$, indicating that there is no difference in the effect of the PBL model on senior high school students' critical thinking skills across research regions. This result is not consistent with the initial assumption that the effect of PBL on improving students' critical thinking skills in Java would be greater than in other islands (Sari & Hardini, 2020), due to the more advanced information and communication technology, as well as the better availability of educational facilities and supporting infrastructure for students in that region compared to other islands in Indonesia (Sari & Hardini, 2020). Based on Table 6, the effect sizes for the Sulawesi and Nusa Tenggara regions are based on only one primary study each. In contrast, the other two regions are based on 11 primary studies and do not cover all regions of Indonesia, so the results are less optimal. Therefore, future research is recommended to analyze a larger number of primary studies to obtain more optimal results.

In Table 6, it can be seen that, by year of study, the grouping was based on the timeline of the COVID-19 pandemic in Indonesia, which began on March 2, 2020, and officially ended on June 21, 2023. Meanwhile, globally, the World Health Organization (WHO) declared COVID-19 a pandemic on March 11, 2020, and it ended on May 5, 2023. The analysis of the year of study in this research was conducted based on the periods before, during, and after the pandemic. This was done because, during the pandemic, several policies were implemented across society, including in education. Policies implemented during the pandemic in education included online learning, limited face-to-face learning, and even temporary school closures. The purpose of this analysis is to determine the effect of the COVID-19 pandemic on the magnitude of the effect of the PBL model on the mathematical critical thinking skills of senior high school students, and also to provide insights in the field of education to make more informed decisions in selecting learning models during and after experiencing similar situations in the future.

Based on the year of study, the effect size in the COVID-19 pandemic group falls within the moderate range. In contrast, the effect sizes in the groups before and after the COVID-19 pandemic fall into the very large effect category. This indicates that the implementation of PBL during the pandemic tends to be less effective compared to before and after the pandemic in improving the mathematical critical thinking skills of senior high school students. The Z-test results in Table 6 indicate that the p-value for the group during the Covid-19 pandemic differs from those of the other groups ($p > 0.05$), suggesting that the effect of PBL on improving students' mathematical critical thinking skills is not significant during the Covid-19 pandemic. These results are supported by differences between the pandemic and pre- and post-pandemic periods: during the pandemic, learning was often conducted online, whereas in the pre- and post-pandemic periods, it was conducted offline. This aligns with the findings of Putra et al. (2021), which indicate that 95% of students show high interest in learning when it is conducted offline, whereas during online learning, 62% show low learning interest. However, the heterogeneity test of the three groups based on the year of study yielded a p-value of $p > 0.05$, indicating that there is no significant difference in the magnitude of the PBL model's effect on senior high school students' critical thinking skills across the three study-year groups.

CONCLUSION

The findings of this study indicate that implementing the PBL model has a positive and significant effect on the mathematical critical thinking skills of senior high school students compared to conventional learning models. The analysis based on effect size categorization shows that the PBL model is highly suitable for use across all sample sizes and research regions. However, during the COVID-19 pandemic, when learning was conducted online, PBL was not recommended for improving the mathematical critical thinking skills of senior high school students. Nevertheless, the analysis based on the heterogeneity test indicates that there is no significant difference in the magnitude of the PBL model's effect on students' mathematical critical thinking skills across sample size, region, and year of study.

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