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Problem-Based Learning: Its Effect on Students' Critical Thinking Abilities in Mathematics and Sciences Learning: A Meta-Analysis

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Abstract: Several meta-analysis studies related to the implementation of problem-based learning (PBL) to cultivate students' critical thinking abilities (CTA) have been carried out widely by some researchers. However, they do not focus on the PBL implementation for students' mathematical and sciential critical thinking abilities. Therefore, this study aims to summarize and estimate the PBL effect on the CTA of students in sciences and mathematics learning. Meta-analysis was employed to carry out this study by selecting the random effect model. The CMA was applied to analyze all data. The synthesis of forty primary studies published in 2015 – 2020 and indexed by Sinta, Google Scholar, Scopus, and Web of Science showed that the size of the PBL effect on the CTA of students in mathematics learning was g = 0.769 and it was classified as a moderate effect. Meanwhile, the size of the PBL effect on the CTA of students in sciences learning was g = 1.122 and it was classified as a strong effect. Moreover, PBL affected students' CTA in mathematics learning significantly. Also, it significantly affected students' CTA in science learning. These findings interpret that the PBL implementation in sciences and mathematics learning is effective to enhance CTA of students. Therefore, mathematics and sciences teachers should select it as one of the alternative mathematics and sciences learnings to cultivate their students' CTA.

Keywords: critical thinking abilities, mathematics learning, meta-analysis, problem-based learning, science learning.

基于问题的学习：它对数学和科学学习中学生批判性思维能力的影响：元分析

摘要: 一些研究人员广泛开展了多项与实施基于问题的学习（PBL）以培养学生批判性思维能力（CTA）相关的元分析研究。然而，他们并不关注学生数学和科学批判性思维能力的 PBL 实施。因此，本研究旨在总结和估计 PBL 对科学和数学学习学生 CTA 的影响。通过选择随机效应模型，采用元分析进行本研究。应用 CMA 来分析所有数据。2015-2020 年发表并由辛塔、谷歌学术、斯科普斯和科学网索引的 40 项初级研究的综合表明，PBL 效应对学生数学学习 CTA 的影响大小为 g = 0.769，归类为中等效果。同时，PBL 效应对科学学习学生 CTA 的影响大小为 g = 1.122，被归类为强效应。此外，PBL 显着影响学生在数学学习中的 CTA。此外，它显着影响了学生在科学学习中的 CTA。这些发现解释了在科学和数学学习中实施 PBL 可以有效提高学生的 CTA。因此，数学和科学教师应将其选为替代数学和科学学习之一，以培养学生的 CTA。

关键词: 批判性思维能力、数学学习、元分析、基于问题的学习、科学学习。

1. Introduction

Critical thinking ability (CTA) is an exploration of the thinking process carefully to clarify the understanding of every individual and create smarter

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decisions [1], [2]. It is one of the important 21st – century skills that students should have to adapt to the change of unpredictable situations [3], [4]. The unpredictable situation is such as the fast development of science and technology. The situation requires every student to equalize between their adaption skills and every appearing possibility. So, students' CTA, one of the essential adaption skills, should be cultivated in every learning such as in mathematics and sciences learning.

In mathematics and sciences learning, teachers often implement problem-based learning (PBL) as one of the alternative learnings to cultivate students' CTA. It is a student-centered learning approach facilitating students to integrate theory and practice, apply knowledge and skill and conduct research in determining the best solution to a certain problem [5]. It has some advantages in developing and enhancing students' competence and skill in learning. It supports students' problem-solving skills [6]–[8], students' critical thinking skills [9]–[11], and students' collaborative skills [12]. Also, its design is able to develop CTA of students so that it can create them as critical individuals in verifying, clarifying, and justifying the truth of information such that they can adapt in various situations [13]–[15]. Therefore, it is often used by teachers to be implemented in mathematics and sciences classrooms.

Several empirical studies related to the PBL implementation in mathematics and sciences learning have been carried out by some researchers. They reported that PBL had a positive effect significantly on the students' CTA in mathematics classroom [16]–[20] and sciences classroom [21]–[23]. However, another researcher revealed that the PBL implementation did not affect significantly students' CTA in mathematics learning [24]–[26] and sciences learning [27]. These reports indicate that the PBL effect on the CTA of students in sciences and mathematics is not consistent. Meanwhile, mathematics and sciences teachers need clear and accurate information related to what does PBL affect significantly students' CTA in mathematics and sciences learning? Therefore, to provide clear and precise information, a method that can synthesize some similar quantitative primary study is needed.

Meta-analysis is one of the methods that can be believed to provide a solution to these problems because it gives strong evidence in rejecting and accepting hypotheses, and strict methodology in the synthesis process [28]. Also, it is more detect and decreases bias and better estimates population parameters than other methods [29]. It is a series of statistical methods integrating the various result of the quantitative primary study to generate summarization, estimation, and evaluation of empirical evidence on a certain topic using effect size [30]–[32]. Thus, these advantages of the meta-analysis can provide a valid summarization, estimation, and evaluation related to the PBL effect on the CTA of students in sciences and mathematics classroom.

Several meta-analysis studies related to the PBL effect on the CTA of students in mathematics classroom have been conducted by some researchers [9]–[11]. However, they have not studied the PBL effect on the CTA of students in sciences classroom. Moreover, they have not provided a comparison of CTA between students getting PBL in mathematics classrooms and students getting PBL in sciences classrooms. Therefore, this current study summarizes and estimates the PBL effect on the CTA of students in sciences and mathematics learning. In addition, this study compares CTA between students obtaining PBL in mathematics learning and students obtaining PBL sciences learning. This study contributes to providing clear and accurate information related to the inconsistency of the PBL effect on the CTA of students to mathematics and sciences teachers.

2. Method

Meta-analysis was employed to carry out this study by selecting the random effect model [30]. As revealed in [33] and [34], there were seven steps to conduct a meta-analysis study. These steps are presented in Figure 1.

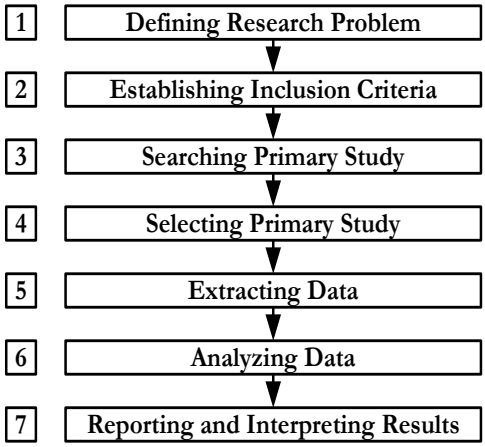


Fig. 1 The steps of the meta-analysis study

2.1. Inclusion Criteria

In establishing the inclusion criteria, we used PICOS (Population, Intervention, Comparator, Outcome, Study design) approach [35]. The inclusion criteria of this study were as follows:

1. Every study provided statistical data completely.
2. Every study was journal or proceeding published in 2015 – 2020 and indexed by Scopus, Google Scholar, Web of Science, and Sinta.
3. The study design of the study was quasi-experiment by selecting posttest only control group design.
4. The outcome of the study was students' CTA in mathematics and sciences learning.

5. The comparator of the study was conventional learning (CL).
6. The intervention of the study was PBL.
7. The population of the study was primary & secondary school students, and college students in Indonesia.

Primary studies that were not suitable to the inclusion criteria would be excluded from this study process.

2.2. The Search of Primary Study

We used Semantic Scholar and Google Scholar to find primary studies. Also, some keywords such as "problem-based learning and mathematical critical thinking ability" or "problem-based learning and scientifical critical thinking ability" or "problem-based learning and chemical critical thinking ability" or "problem-based learning and physical critical thinking ability" or "problem-based learning and biological critical thinking ability" were employed to ease in searching primary studies. Thus, the search engines and keywords supported this study in finding primary studies.

2.3. Selection of Primary Study

We selected every primary study obtained from the search process. This study applied four steps to select every primary study that was: (1) identification, (2) screening, (3) eligibility, and (4) inclusion [35]. Every primary study was selected based on the title of the study in the identification step, based on the abstract in the screening step, based on the inclusion criteria in the eligibility step, and based on publication bias in the inclusion step.

2.4. Data Extraction

Numerical and categorical data such as citation, statistical data (t-value, p-value, mean, standard deviation (SD), and sample size (N)), scientific field, journal or proceeding name, publisher, indexer, publication type, publication year, and search engine were transferred from every primary study to the coding sheet. We communicated with the authors via email to complete the data. Also, we involved two coders to verify and justify that the data extracted was valid [36]. To measure the consistency of data extraction results carried out by two coders, we employed Cohen's Kappa test. Cohen's Kappa values obtained were interpreted as k = 0 – 0.20 (none), k = 0.21 – 0.39 (minimal), k = 0.40 – 0.59 (weak), k = 0.60 – 0.79 (moderate), k = 0.80 – 0.90 (strong), and k > 0.90 (almost perfect) [37].

2.5. Data Analysis

To measure the effect size of PBL on the students' CTA, we used Hedge's equation [30], because it accommodated the relatively small sample size [38]. Every effect size value was classified as g = 0 – 0.20 (weak effect), g = 0.21 – 0.50 (modest effect), g = 0.51 – 1.00 (moderate effect), and g > 1.00 (strong effect) [39]. In addition, we conducted a publication bias test using Rosenthal's fail-safe N (FSN) test to verify that the effect size collection was resistant to publication bias [40]. Also, to verify normality and stability of the effect size collection, we carried out analysis of sensitivity utilizing the "one study removed" tool on Comprehensive Meta-Analysis (CMA) software [41]. Furthermore, to examine the significance of the PBL effect on the CTA of students in sciences and mathematics learning, we used the Z test [30]. Finally, we conducted the Q Cochrane test to examine the significance of the difference of CTA between students obtaining PBL in mathematics learning and students obtaining PBL in sciences learning [42].

3. Results and Discussion

3.1. Search and Selection of Primary Study

We found 247 primary studies from Google Scholar and 358 primary studies from Semantic Scholar by using these keywords. Furthermore, the selection process of these primary studies is presented in Figure 2.

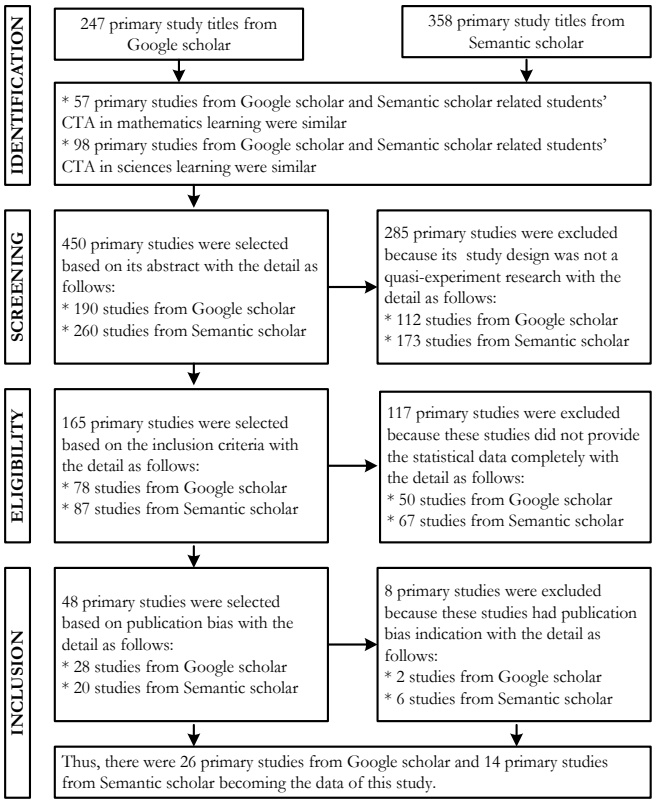


Fig. 2 The selection process of primary studies

We obtained 14 primary studies in Semantic Scholar; these studies related to the PBL effect on the CTA of students in mathematics classroom. Also, there were 19 studies related to the PBL effect on the CTA of students in sciences classroom, and 7 studies related the PBL effect on the CTA of students in mathematics classroom from 26 primary studies obtained in Google scholar.

3.2. Data Extraction

The results of Cohen's Kappa test are presented in Table 1.

Table 1 Cohen's Kappa value of every item

Item	Kappa Value	Agreement Level	Significance Value
Citation	0.834	Strong	0.004
Mean of PBL group	0.925	Almost perfect	0.012
SD of PBL group	0.913	Almost perfect	0.023
Sample size of PBL group	0.972	Almost perfect	0.035
Mean of CL group	0.957	Almost perfect	0.025
SD of CL group	0.971	Almost perfect	0.038
Sample size of CL group	0.965	Almost perfect	0.009
t-value	0.981	Almost perfect	0.001
p-value	0.939	Almost perfect	0.003
Scientific field	0.871	Strong	0.023
Publication type	0.864	Strong	0.035
Publication year	0.896	Strong	0.027
Search engine	0.812	Strong	0.013
Journal and proceeding name	0.796	Moderate	0.042
Publisher	0.723	Moderate	0.048
Indexer	0.775	Moderate	0.041

The agreement level of two coders on every item was classified as moderate agreement, strong agreement, and almost perfect agreement. Table 1 reveals that every p-value of the Z statistic of every item was less than 0.05. The findings indicate that two coders significantly agree on every item that is numerical and categorical data transferred from every primary study to the coding sheet.

Primary studies were journals or proceedings. The detail of the publication type of every primary study is presented in Figure 3.

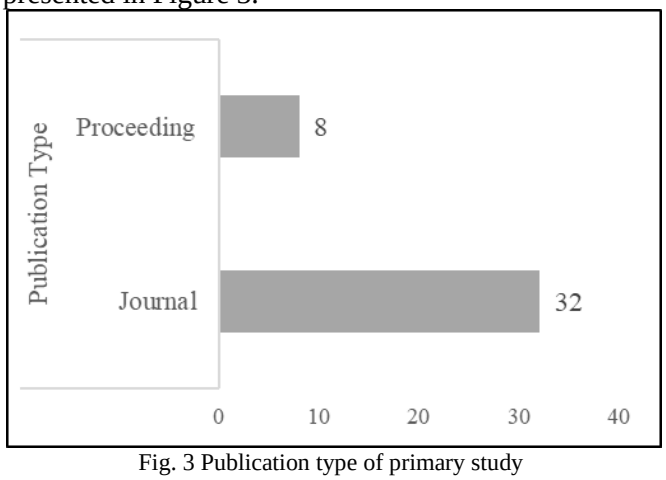


Fig. 3 Publication type of primary study

Figure 3 reveals that the primary study consisted of 32 journal articles and 8 proceeding articles. It indicates that the study in journal articles is more dominant than the study in proceeding articles.

The studies were published in 2015 – 2020. The detail of the publication year of every primary study is presented in Figure 4.

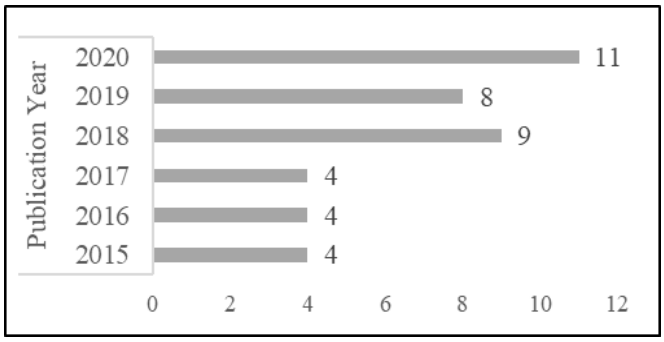


Fig. 4 Publication year of primary study

Figure 4 shows that the trend of research related to the PBL implementation on the CTA of students in sciences and mathematics classroom increased from year to year. It indicates that the PBL implementation in sciences and mathematics classrooms is more massive from year to year.

Primary studies were indexed by some indexers such as Scopus, Google Scholar, Sinta, and Web of Science. Figure 5 reveals that there were two studies indexed by Web of Science, nine studies indexed by Scopus, ten studies indexed by Google Scholar, and nineteen studies indexed by Sinta. It interprets that primary study indexed by Sinta is more than primary study indexed by Scopus, Google Scholar, or Web of Science. The detail of the indexer of every primary study is presented in Figure 5.

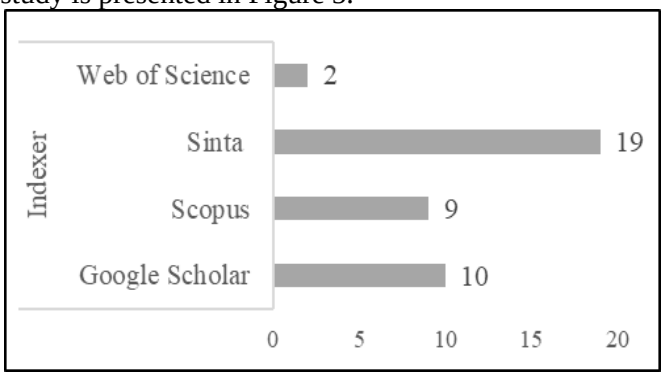


Fig. 5 The indexer of primary study

3.3. Sensitivity and Publication Bias

The "one study removed" tool on CMA application reported that the lowest effect size was g = 0.910 and the highest effect size was g = 1.020. Meanwhile, the overall mean of effect size was g = 0.935. The findings showed that the overall effect size mean was located between the lowest effect size and the highest effect size. It interprets that the effect size collection is normal and stable on the change of effect size and sample size. It means that the effect size collection is not sensitive [41].

Furthermore, the results of Rosenthal's FSN test are presented in Table 2.

Table 2 The results of the FSN test

Classic Fail-Safe N	
Z-value	21.591
P-value	0.000
FSN value	4.815

Table 2 reveals that the FSN value was 4.815. It indicates that this study needs 4.815 null effect sizes so that the p-value is possible to exceed α = 0.05. Moreover, the p-value of the Z statistic was less than 0.05. It interprets that the effect size collection is resistant to publication bias. It means that the collection of effect size does not indicate publication bias [40].

3.4. The Overall PBL Effect Size on the CTA of Students in Sciences and Mathematics Learning

Figure 6 shows that the overall PBL effect size on the CTA of students in mathematics learning from 21 primary studies synthesized was g = 0, 769 and it was classified as a moderate effect [39]. Also, the p-value of the Z statistic of the mathematics group was less than 0.05. It interprets that the PBL implementation affects significantly students' CTA in mathematics learning. Several meta-analysis studies also revealed that PBL had a positive effect significantly on the mathematical critical thinking skills of students [9]–[11]. These reports support strong evidence that the PBL implementation is effective to enhance CTA of students in the mathematics classroom. The summarization and estimation of the PBL effect size on the CTA of students in mathematics and sciences learning are presented in Figure 6.

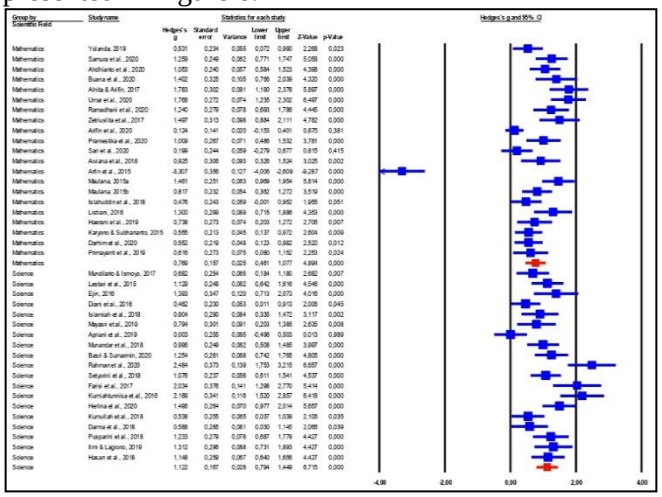


Fig. 6 The overall PBL effect size on the CTA of students in mathematics and sciences learning

In addition, Figure 6 shows that the overall PBL effect size on the CTA of students in sciences learning from 19 primary studies synthesized was g = 1.122 and it was classified as a strong effect [39]. This finding was similar to a previous meta-analysis study revealing that the PBL effect size on the student's critical thinking skills was ES = 1.36 (physic), ES = 1.20 (chemistry), and ES = 1.08 (biology) [43]. These effect sizes were categorized as a strong effect [39]. Moreover, the p-value of the Z statistic of the sciences group was less than 0.05. It indicates that the PBL implementation affects significantly students' CTA in sciences learning. It means that the PBL implementation is effective in enhancing CTA of students in the sciences classroom.

The significance of PBL in enhancing CTA of students in sciences and mathematics classroom because of PBL is a learning approach designed to enhance the learning quality by developing students' collaborative and critical thinking skills [12]. Also, one of the characters of PBL is cooperative learning [5], [44], [45]. The synthesis result of some studies revealed that students' academic achievement can be improved when students collaborate in a cooperative learning environment [46]. Therefore, students' CTA enhances by implementing PBL because it is cooperative learning.

Several theoretical studies reported that PBL is one of the learning models supporting the cultivation of student's critical thinking skills [13], [14], [47]. Also, PBL is a learning approach promoting the improvement of higher-order thinking skills such as critical thinking and creative skills [48]. Development of the student's critical thinking skills is by stimulating some problems given to them in the learning process [5], [49]. These problems require them to think creatively and critically in solving them so that they can find concepts and principles from mathematics and sciences learning by solving these problems. It means that indirectly PBL implementation process in mathematics and sciences learning stimulates students to cultivate their CTA.

3.5. The Comparison of Student' CTA in Mathematics and Sciences Learning through PBL

Table 3 reveals that the p-value of the Q Cochrane statistic was more than 0.05. It interprets that there is no significant difference in CTA between students obtaining PBL in mathematics learning and students obtaining PBL in sciences learning. Also, as revealed in [50], there was no significant difference in academic achievement between students getting PBL in mathematics classrooms and students getting PBL in sciences classrooms. It means that significantly the PBL effect on the CTA of students in mathematics learning is not different from the PBL effect on the CTA of students in sciences learning. The results of the Q Cochrane test are presented in Table 3.

Table 3 The results of heterogeneity analysis

Group	Number Studies	Effect Size	Heterogeneity Analysis		
			Q-value	df(Q)	P-value
Mathematics	21	0.769	2.359	1	0.125
Sciences	19	1.122			

Descriptively the PBL effect on the CTA of students in sciences learning was greater than the PBL effect on the CTA of students in mathematics learning. Moreover, it was reported in [50] that the overall PBL effect size on the academic achievement of students in mathematics classrooms from 15 primary studies synthesized was g = 0.86 (moderate effect). Also, the overall PBL effect size on the academic achievement of

students in the sciences classroom from 58 primary studies synthesized was g = 0.90 (moderate effect). It also indicates that the PBL effect on the academic achievement of students in mathematics learning was lower than the effect of PBL on the students' academic achievement in the sciences classroom. It means that in developing students' CTA, the PBL implementation in the sciences classroom is more effective than the PBL implementation in the mathematics classroom.

4. Conclusion

This study provides some information related to the PBL effect on the CTA of students in sciences and mathematics learning. Overall, PBL has a moderate effect in enhancing students' CTA in the mathematics classroom. Meanwhile, PBL has a strong effect in improving students' CTA in the sciences classroom. In addition, the implementation of PBL affects students' CTA positively in mathematics and sciences learning. Therefore, teachers of mathematics and sciences should select it as one of the alternative learning in the classroom to develop their students' CTA. Furthermore, there is no significant difference in critical thinking skills between students obtaining PBL in the mathematics classroom and students obtaining PBL in the sciences classroom. However, descriptively, to develop students' CTA, the PBL implementation in the sciences classroom is more effective than the PBL implementation in the mathematics classroom. This study has not investigated and examined some potential factors causing the heterogeneity of students' mathematical and scientific critical thinking abilities through PBL. So, for further meta-analysis study regarding a similar topic, this study recommends other researchers to investigate and examine the causative factor of the heterogeneity of students' CTA by implementing PBL such as PBL class capacity, PBL treatment duration, and students' demography.

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