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The Role of Problem-Based Learning in Developing Science Literacy and 21st-Century Skills in High School Students: A Meta-Analysis

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Abstract

This study aims to analyse the role of the Problem-Based Learning learning model in developing science literacy and 21st-century skills in science learning for students from junior high to high school levels. This study uses a quantitative model with a meta-analysis method. The source of research data was obtained from the analysis of national and international articles indexed by SINTA, Google Scholar, Eric, and Scopus. The articles sampled were national and international articles published between 2020 and 2024, with a total of 36 articles. Sample selection was carried out through searches on Google Scholar, Eric Journal, and Scopus using the Publish or Perish application and purposive sampling techniques. The research sample was selected through a purposive sampling technique, with a focus on an article that discusses the role of the Problem-Based Learning learning model in developing science literacy and 21st-century skills in science learning for junior and senior high school students. Data analysis was carried out using Microsoft Excel software and JASP 0.18.2.0. The data produced shows that the average score of science literacy and skills in the 21st century increased. The results of the study prove that Problem-Based Learning (PBL) is very effective in developing science literacy and 21st-century skills in science learning in high school students. Thus, meta-analysis research makes the problem-based learning model an innovative learning model to support educational transformation in developing science literacy and 21st-century skills in high school students.

Keywords: Problem-Based Learning, Science Learning, Scientific Literacy, 21st Century Skills, Meta-Analysis

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INTRODUCTION

Currently, the world has entered the 21st century, which, of course, brings its challenges. Humans are required to have 21st-century skills in order to compete in daily life (Berliana, Suwarma, and Novia, 2024). Education plays an important role in ensuring the survival of the nation because one of the goals of education is to give birth to a young generation who have certain skills and are able to face world problems. In the 21st century, the advancement of science and technology in various countries is growing rapidly (Biruni et al., 2023). Science literacy is one of the 21st-century skills that students need to have. One of the things that affects students' science literacy ability is the learning model used (Setiaji, 2018). This study aims to determine the influence of the Problem-Based Learning (PBL) learning model on science literacy and 21st-century skills of high school students (Parno et al., 2020). Science literacy is one of the skills that must be possessed in the 21st century; it is necessary to pay attention to its development so that educational activities can aim to create a society that has science literacy (Berliana et al., 2024). The 21st century shows that the development of information moves very quickly. Everyone must be able to understand the aspects of science and its problems in the modern era (Karimiz & Winarso, 2021).

The Problem-based learning (PBL) model is an effective learning model in improving science literacy among students, and this strategy helps students acquire and apply knowledge and find out the influence of the role of Problem-based learning (PBL) on students' science literacy (Training and Arts 2024). Science literacy is the scientific ability of students to solve problems and explain scientific phenomena (Adiwiguna, Dantes, and Gunamantha 2019). In science learning, students must have high science literacy. According to (Alatas and Fauziah 2020), Indonesia's science literacy level is still low, with a ranking of 71 out of 79 countries participating in PISA (Lestari, Putri, and Azhar 2024). Therefore, it is necessary to improve the learning models and methods used by teachers (Ichsan 2022). Related to 21st-century skills and science literacy, these are important competencies that students must possess. However, student science literacy in Indonesia is still very low (Parno et al. 2020). The low science literacy of Indonesian students in science materials is caused by several factors, including learning models that are still too textual and conventional (Putri, Sudarisman, and Ramli 2014). Students with high science literacy are able to relate science concepts to daily life.

In science learning, science literacy must be encouraged so that students are confident and can connect science literacy with learning materials (Anggreni, Jampel, and Diputra 2020). In accordance with the purpose of science education it is to educate students to be able to adapt to various conditions, think flexibly, ask questions, be creative, think critically, respect society, and be tolerant of ideas (Agussuryani et al. 2022). For this reason, teachers need to adopt the right learning model. The Problem-Based Learning (PBL) model is one of the effective models for improving students' science literacy (Dewi, Kuswanti, and Prijono 2023). PBL is based on problem-solving that requires authentic investigation (Parwasih and Warouw 2020) and proven to improve student learning outcomes and motivation (Azis, Lutfi, and Ismail 2018). Science literacy is one of the competencies that students must have in the 21st-century era, so to find out the improvement of students' science literacy skills through the role of the problem-based learning model (Pakpahan 2022). The importance of science literacy and 21st-century skills in the field of education, making science literacy a standard for measuring the quality of science education (Pakpahan 2022) Everyone is required to master literacy and mastery of concepts (Putri and Indana 2019). However, the reality in Indonesia regarding science literacy skills in students is still relatively low. In fact, with science literacy skills, a person can overcome problems in daily life (Putri and Indana 2019).

This study uses meta-analysis, namely by combining the results of various studies, to increase statistical strength, expand generalisations, overcome variations between studies, reduce publication bias, and provide hypothesis testing and stronger moderation factor identification. Based on the existing literature, some findings show that the role of the Problem-Based Learning learning model in developing science literacy and 21st Century skills in science learning for students from junior high to high school in the context of science education provides positive results (Strobel and van Barneveld 2009). However, challenges in implementing PBL, such as time and resource constraints, as well as differences in student characteristics, can affect the results achieved (Hung 2012). Therefore, it is important to systematically evaluate how these variables contribute to the results obtained through the role of problem-based learning (PBL) models (Noordzij and Wijnia 2020). So this meta-analysis research will combine findings from various studies to provide a clearer picture of the role of PBL in developing science literacy and skills in the 21st century (Illene, Feranie, and Siahaan 2023).

METHOD

This study uses a quantitative model and meta-analysis method. Meta-analysis is a type of research that collects and analyses quantitative data that can be calculated statistically. The data sources for this research come from national and international articles indexed in SINTA, Google Scholar, Science Direct, and Scopus. The sample used consisted of national and international articles published between 2020 and 2024, with a total of 36 articles. The sample search process is carried out through Google Scholar, ERIC Journal and Scopus using the Publish or Perish application. The sampling technique used is purposive sampling, which is to select articles that are relevant to the research topic regarding the influence of the Problem-Based Learning learning model on science literacy and 21st-century skills in junior high to high school students. The research method uses a literature review with a modified procedure from systematic review and meta-analysis (PRISMA). The procedure consists of identification, screening, feasibility, and inclusion. The research procedure is shown in Figure 1.

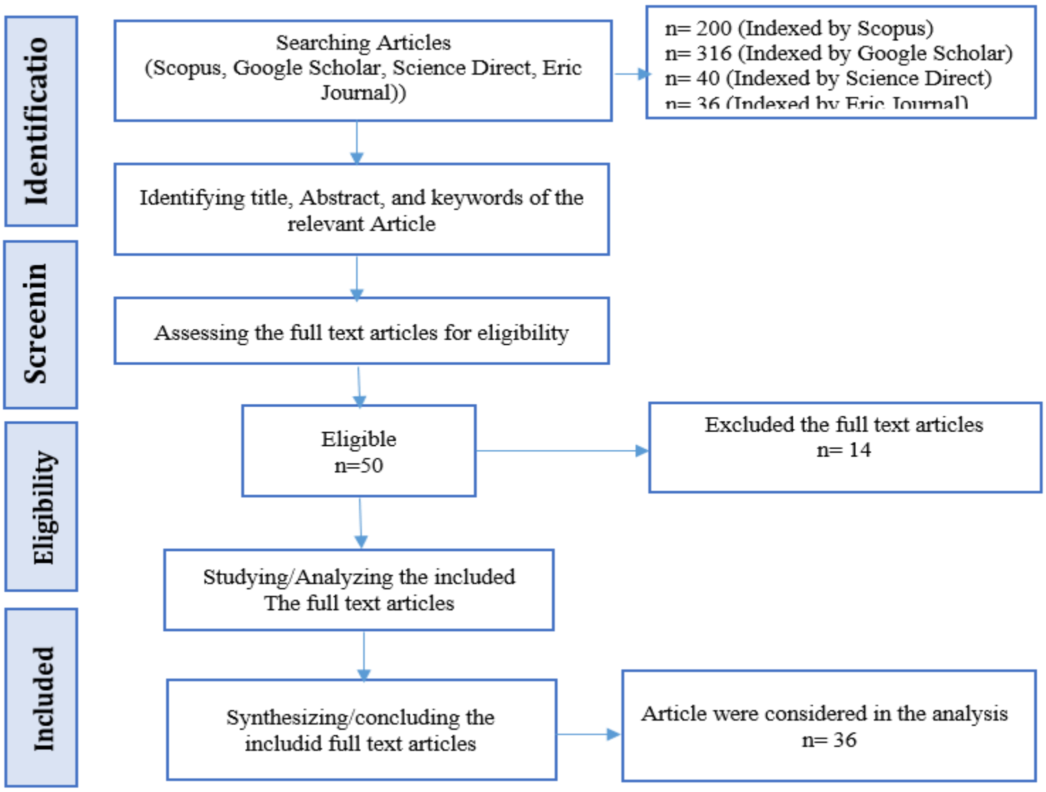

Figure 1. PRISMA Method Research Procedure

Meta-analysis is carried out by collecting relevant research data. The search for the article uses the keyword "Problem-Based Learning, Science Literacy and Skills in the 21st Century". The articles are selected for analysis, and then codes NA1, NA2, and so on are assigned to NA36. Data analysis uses Effect Size (ES) values with a group contrast model, which includes estimation of effect size, variance, and Standard Error (SE) values, as well as interpretation of the analysis results. This meta-analysis aims to determine the effect of the use of the PBL model on science literacy ability based on the number of research subjects, the average score of the pretest, posttest, and standard deviation. The calculation was done using Microsoft Excel, and the results were interpreted based on Cohen's guidelines, namely ES = 0.20 as a small effect, ES = 0.50 as a medium effect, and ES = 0.80 as a large effect (Setyasih, Rusdi, and Ristanto 2022). For data analysis, this study combines quantitative and qualitative analysis techniques with the help of Microsoft Excel and JASP 0.18.2.0 software—effect size analysis 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

RESULTS AND DISCUSSIONS

From the results of a meta-analysis of national and international articles that have been indexed by SINTA, Google Scholar and Eric Journal, 36 articles have been analysed related to the relationship between the role of the Problem-Based Learning learning model in developing science literacy and 21st Century skills in science learning in students from junior high to high school levels in science materials consisting of Biology material, Chemistry and Physics which has been published for the last 5 years, from 2020 to 2024. The results of the meta-analysis can be seen in Table 2.

The results of the data analysis are in the table.2 shows that the application of the Problem-Based Learning (PBL) learning model has a significant impact on improving students' science literacy and 21st-century skills. Data from 36 studies summarised in the table showed a consistent increase between pretest and posttest scores. The average posttest score of students was higher than the pretest score in all studies. For example, in the study, the student's pretest score increased from 54.16 to 75.46 on the post-test. The effect of the PBL application was also reflected in the effect size (ES) value, which varied between 0.72 and 0.96, with an average of 0.84. According to Cohen's interpretation, this average falls into a large category, indicating a significant impact of PBL on student learning outcomes.

Based on the results of descriptive statistical analysis, there was a significant improvement in student learning outcomes after the implementation of the Problem-Based Learning (PBL) learning model. The data showed that the median increased from 66,000 in the pretest to 80,000 in the posttest, while the mean also increased from 64,838 to 79,595. This indicates an improvement in the performance of the majority of students. In addition, the standard deviation decreased from 7,737 to 6,383, which means that the post-test results are more consistent than the pretest. The decrease in variance from 59,862 in the pretest to 40,748 in the posttest further supports the conclusion that learning outcomes are more focused after the implementation of PBL. The score range in the pretest is 33 (with a minimum score of 46 and a maximum of 79), while in the posttest, the range narrows to 26 (minimum 67 and maximum 93), indicating a more centralised result. Negative kurtosis values in the pretest (-0.246) and posttest (-0.255) show a flat data distribution. The mean confidence interval (95%) increased from 62,258–67,417 on the pretest to 77,466–81,723 on the posttest, providing high confidence in a significant improvement in students' average scores. Overall, the results of this analysis show that problem-based learning (PBL) not only improves students' average scores but also the consistency of outcomes between participants. These findings confirm the effectiveness of PBL in supporting the development of science literacy and 21st-century skills in science learning.

Table 2. Summary of research data, Pretest, posttest, Effect Size (ES), and Standard Error (SE)

No	Data Code	Pretest	Postest	ES	SE
1	NA1	66.37	70.00	0.96	0.059
2	NA2	55.38	66.92	0.82	0.056
3	NA3	54.26	67.20	0.76	0.054
4	NA4	66.00	75.36	0.81	0.052
5	NA5	60.79	76.97	0.84	0.052
6	NA6	46.09	79.03	0.72	0.050
7	NA7	70.42	82.16	0.88	0.051
8	NA8	59.20	68.60	0.75	0.054
9	NA9	68.42	80.06	0.72	0.047
10	NA10	54.16	75.46	0.83	0.054
11	NA11	75.20	84.40	0.84	0.046
12	NA12	78.57	85.71	0.82	0.053
13	NA13	71.67	88.33	0.86	0.050
14	NA14	78.50	83.30	0.87	0.050
15	NA15	72.10	80.34	0.78	0.060
16	NA16	64.23	80.90	0.80	0.052
17	NA17	74.13	92.74	0.84	0.052
18	NA18	62.20	67.60	0.79	0.053
19	NA19	66.50	87.50	0.82	0.051
20	NA20	67.21	86.00	0.83	0.052
21	NA21	64.44	88.88	0.78	0.050
22	NA22	71.15	84.33	0.84	0.053
23	NA23	70.36	78.86	0.83	0.050
24	NA24	70.28	84.00	0.87	0.058
25	NA25	64.62	78.73	0.80	0.050
26	NA26	60.00	75.00	0.86	0.051
27	NA27	56.64	77.94	0.85	0.055
28	NA28	61.75	76.88	0.76	0.048
29	NA29	72.00	86.00	0.73	0.051
30	NA30	55.13	77.19	0.76	0.050
31	NA31	58.66	73.33	0.77	0.048
32	NA32	67.65	80.54	0.74	0.045
33	NA33	72.10	86.80	0.74	0.048
34	NA34	58.70	76.99	0.88	0.053
35	NA35	68.85	79.03	0.82	0.050
36	NA36	51.09	82.00	0.78	0.046

Table 3. Descriptive Statistics

	Pretest	Postest
Median	66.000	80.000
Mean	64.838	79.595
Std. Error of Mean	1.272	1.049
95% CI Mean Upper	67.417	81.723
95% CI Mean Lower	62.258	77.466
Std. Deviation	7.737	6.383
Variance	59.862	40.748
Kurtosis	-0.246	-0.255
Std. Error of Kurtosis	0.759	0.759
Range	33.000	26.000
Minimum	46.000	67.000
Maximum	79.000	93.000

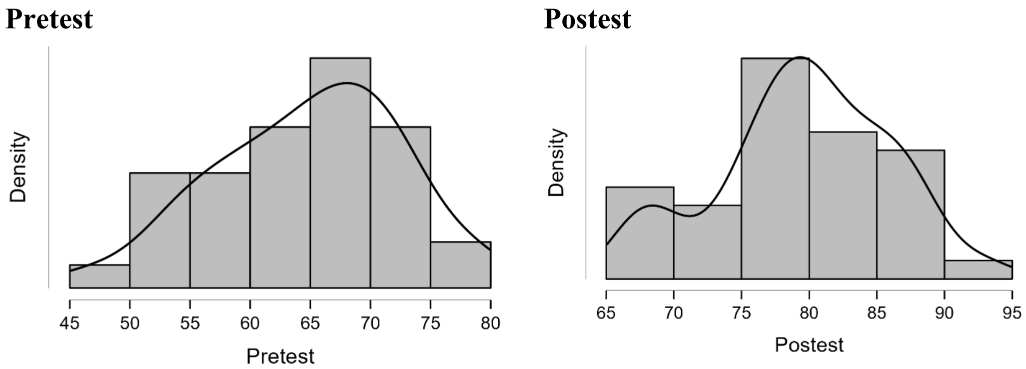

Figure 2. Diagram distribution plots pretest – postest

Based on the analysis of Figure 2 of the Distribution Plots Pretest - Posttest Diagram, the distribution of pretest and posttest scores shows a noticeable change. In the pretest, the distribution tended to spread more widely, with scores concentrated in lower score ranges, indicating that many students were at an early level of 21st-century science literacy and had skills that were still low. In contrast, the distribution of post-test scores shows a significant shift towards higher scores, with a more centralised concentration of data. This reflects the improvement in the performance of the majority of students after the implementation of the Problem-Based Learning (PBL) learning model. The narrower spread of data on the post-test shows more uniform results, which is also supported by a decrease in standard deviation from the pretest to post-test results. The shift of the distribution peak to a higher score in the posttest confirms the effectiveness of PBL in improving student learning outcomes. The more centralised distribution of the posttest also reflects that the majority of students manage to achieve consistently higher levels of understanding and skills.

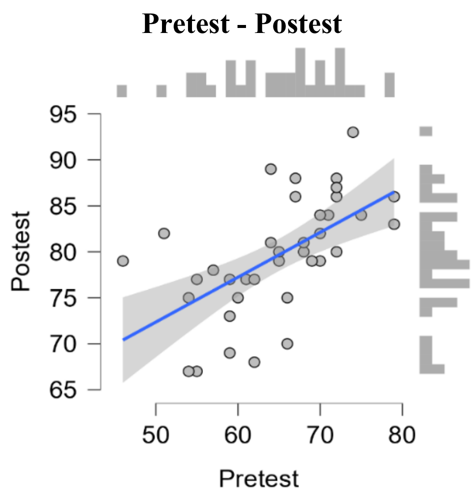

Figure 3. Scatter Plots Pretest-Postest

Based on Figure.3 Scatter Plots Pretest-Posttest, the relationship between pretest and posttest scores shows a consistent upward trend where the majority of data moves towards a higher score on the posttest. The distribution pattern of the points in the plot illustrates that there is a significant improvement in student learning outcomes after the implementation of the Problem-Based Learning (PBL) learning model. In scatter plots, the dots tend to be more concentrated on the posttest axis compared to the pretest axis, which signifies that most students achieve better grades after the problem-based learning process. This improvement indicates that students who initially had low or moderate pretest scores managed to achieve better results, although the level of improvement may vary between individuals. In addition, the distribution of data in the posttest is more centralised, showing more uniform results than the pretest. This positive trend confirms the effectiveness of PBL in improving science literacy and 21st-century skills. This scatter plot provides visual evidence that PBL is able to help students at various early levels of understanding achieve more optimal learning outcomes.

Table 4. Coefficients

					95% Confidence Interval	
	Estimate	**Standard Error**	**z**	**p**	**Lower**	**Upper**
intercept	0.807	0.009	92.201	<.001	0.790	0.824

Note. Wald test.

The results of the analysis in Table 4: Coefficients show that the application of the Problem-Based Learning (PBL) model has a significant positive influence on students' science literacy and 21st-century skills. The average coefficient estimate value of 0.807 indicates that the implementation of PBL has a considerable impact on student learning outcomes. This value is supported by a high degree of precision, with a standard error (SE) of 0.009, which indicates the consistency of results between studies in this meta-analysis. The statistical significance of these results is also very strong, with a value of $z = 92.201$ and $p < 0.001$, which confirms that the average effect of PBL on learning outcomes is real and reliable. In addition, the 95% confidence interval for coefficient estimates ranged from 0.790 to 0.824, indicating a high level of confidence that the average effect was within that range. This narrow interval range also reflects a good level of precision in estimation.

Figure 4: Forest Plot presents a visualisation depicting the effect size of the various studies analysed in this meta-analysis. This forest plot shows the estimated effect size for each study, with a 95% confidence interval (CI) indicating the range of values in which the true effect size is most likely to be. Each horizontal line represents the study being analysed, with the dots indicating the estimated effect size and the lines surrounding it indicating the confidence interval. Overall, this forest plot shows that most studies have a positive effect size, which indicates that the application of Problem-Based Learning (PBL), in general, improves students' science literacy and 21st-century skills (Illene et al., 2023).

The confidence interval that did not include a zero value in most studies showed that this effect was statistically significant. In addition, the diversity in the size of the effect between studies, as seen from the lengths of different confidence intervals, showed variation in the results of the study (Setyasih et al. 2022). However, none of the studies showed very small or negative effect sizes, suggesting that the application of PBL had a consistent positive effect. This forest plot provides a clear picture that the PBL learning model effectively improves students' 21st-century skills and science literacy, with stable results across a variety of contexts and analysed studies. It also confirms that although there is variation in influence between studies, the overall impact of PBL remains significant and supports the conclusion that this method is effective in improving students' abilities.

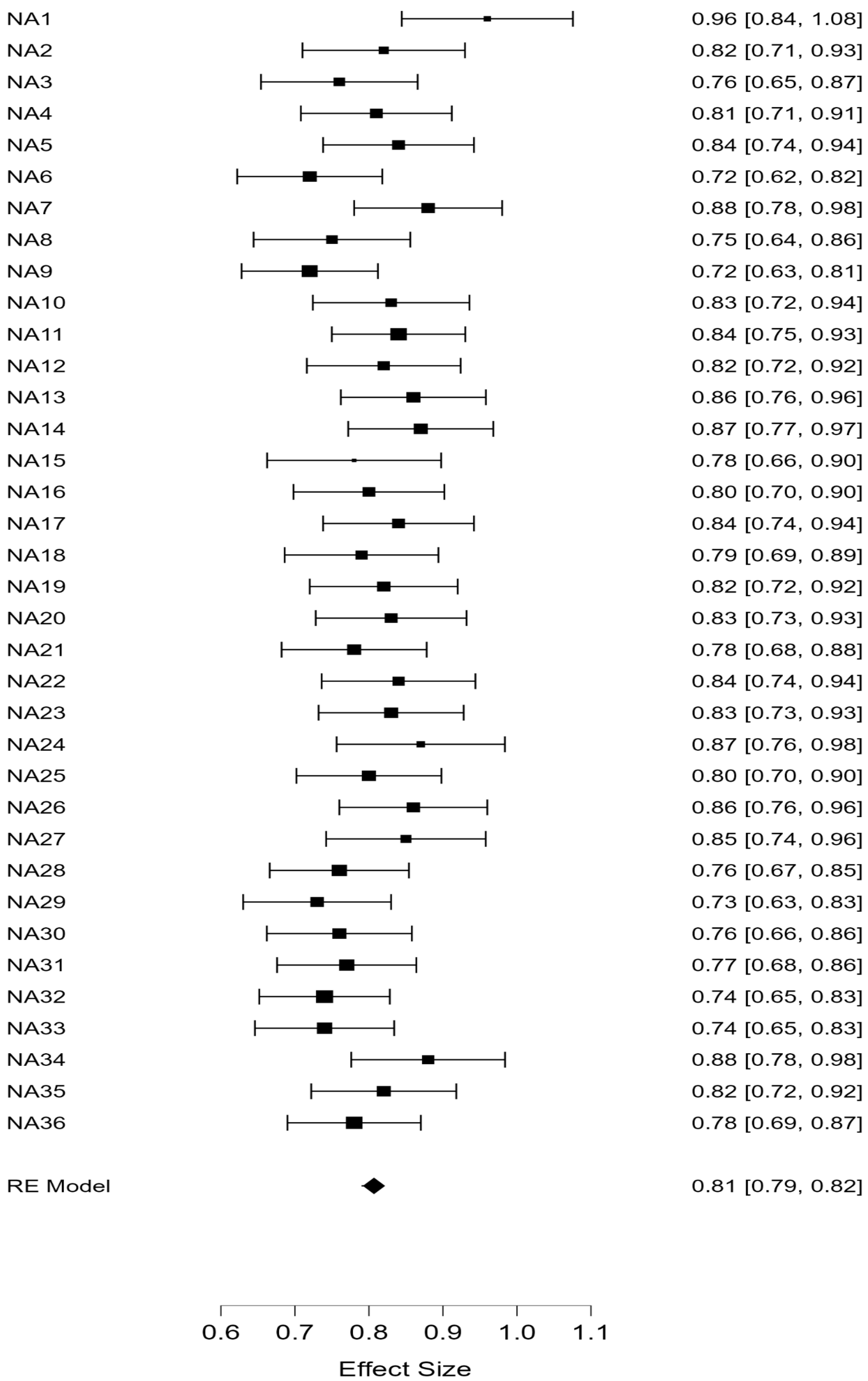

Figure 4. Forest Plot

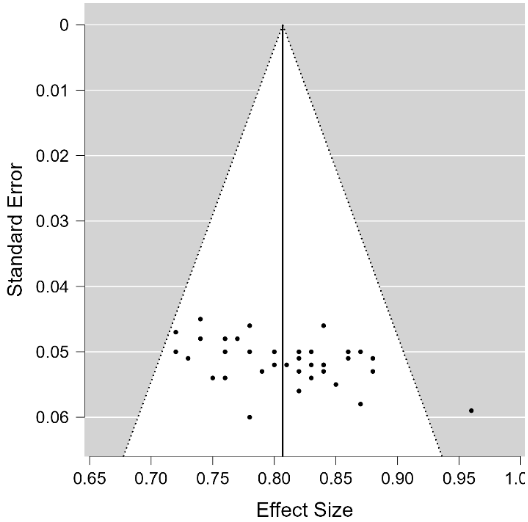

Figure 5. Funnel Plot

Figure 5 Funnel Plot presents a visualisation of the distribution of effect measures from the various studies analysed in this meta-analysis. This plot funnel is used to evaluate potential publication bias by plotting the size of the effect of each study on the sample size. Typically, in a funnel plot that is not affected by publication bias, the data points will be symmetrically spread around the centre vertical line, which represents the average effect. Points farther from the centre line represent studies with smaller sample sizes, while points closer to the centre line come from studies with larger sample sizes. Based on Figure 5, the distribution of data points shows a slight asymmetry on the right side of the plot funnel, which can indicate the potential for publication bias. Publication bias often occurs when studies with significant results are more likely to be published than studies with insignificant results. Nonetheless, this asymmetry is not very striking, which suggests that although there is a possibility of publication bias, its impact on the results of the meta-analysis is not very large.

Figure 6: Trim-fill analysis is a technique used to address potential publication bias in meta-analysis by modifying the plot funnel to estimate how unpublished research results may affect the overall conclusion. Test publication bias can be done using the Trim and Fill method, which shows that there is no publication bias in the meta-analysis conducted. (Arlinwibowo, Retnawati, and Kartowagiran 2022). Trim-fill analysis helps to identify whether any studies are missing or unpublished (publication bias) that could change the mean effect measured. In this analysis, a smaller study with insignificant results was added to the model to "correct" the asymmetry in the funnel plot. In Figure 6, it can be seen that this analysis estimates some missing (or unpublished) data points, represented by points that are added to "fill" in the empty funnel side of the plot. These added points indicate smaller studies that may have insignificant and unpublished results, which could contribute to previously detected plot funnel asymmetry.

By adding these studies, Trim-Fill Analysis corrects asymmetry and provides a more complete picture of the potential bias of publications (Alatas & Fauziah, 2020). Although this analysis shows the presence of some missing studies, the results of the Trim-Fill Analysis show that even after accounting for potential publication bias, the mean effect remains consistent and significant (Dewi et al., 2023). This indicates that the application of Problem-Based Learning (PBL) continues to have a positive influence on students' science literacy and 21st-century skills. However, there is a potential for publication bias that may affect the distribution of data (Tamam, Sudibyo, and Negeri Surabaya, 2023). Therefore, the impact of the overall PBL model on student learning outcomes is not significantly distorted by missing or unpublished studies (Sekti, Murti, and Nurudin 2021).

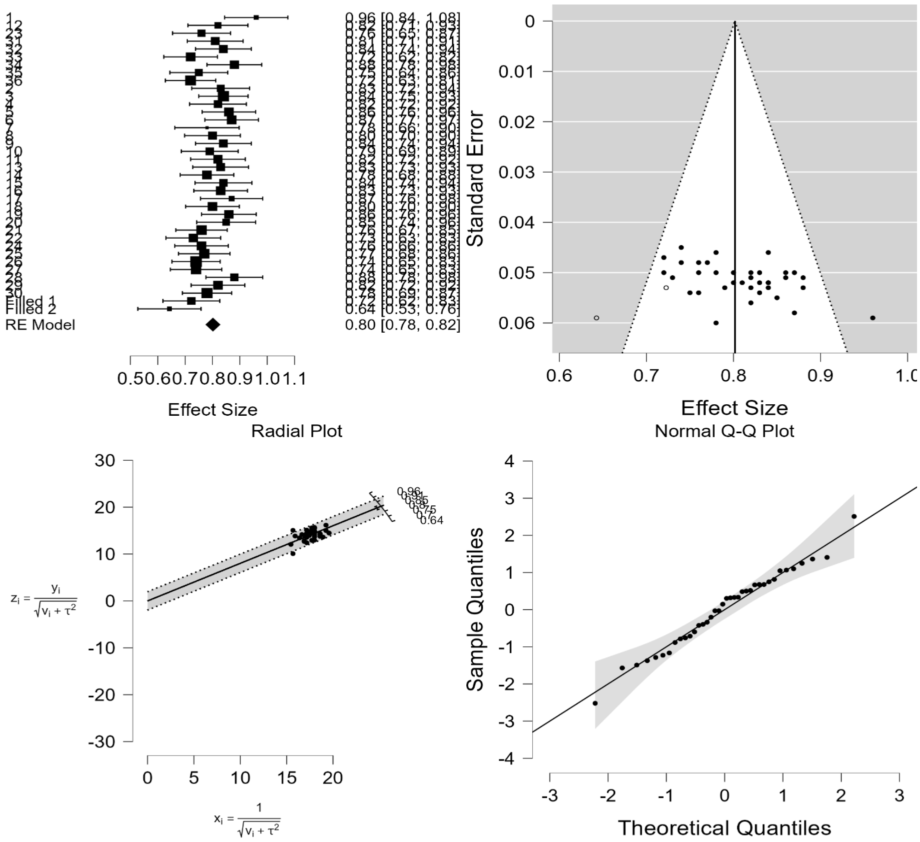

Figure 6. Trim-Fill Analysis

In addition, the results of the Trim-Fill Analysis also showed that the confidence interval for the mean effect remained within a reliable range, even after accounting for missing studies. It confirms that while publication bias may exist, it is not strong enough to change the main conclusions of the meta-analysis (Putri et al., 2014). These findings provide confidence that the application of PBL is effective in consistently improving students' science literacy and 21st-century skills across the analysed studies. Overall, Figure 6: Trim-Fill Analysis confirms that although publication bias may affect the distribution of data in the plot funnel, the overall effect of PBL application on students' 21st-century science literacy and skills remains significant and reliable (Nainggolan, Situmorang, and Hastuti 2021). This reinforces the results of the meta-analysis, suggesting that despite potential bias, this problem-based learning model remains effective in consistently improving student learning outcomes across the different studies analysed (Lailis Indriani et al., 2023).

This study shows that the application of Problem-Based Learning (PBL) has a significant impact on improving students' science literacy and 21st-century skills (Ardianto & Rubini, 2016), with an average score of 72.22 and an effect size (ES) of 0.52, which is included in the medium category. These results are consistent with previous research that identified that PBL can improve students' critical thinking skills and science literacy (Anggreni et al., 2020)-(Ichsan, 2022). PBL provides opportunities for students to develop 21st-century skills such as collaboration, creativity, communication, and critical thinking, which are crucial in this ever-evolving world (Wardani & Fiorintina, 2023). These findings reinforce the importance of using PBL as a relevant model in science education (Sugiarti et al., 2021). One of the main advantages of PBL is its ability to encourage students to think critically and solve problems relevant to daily life (Wardani & Fiorintina, 2023). This model makes students more involved in the learning process and encourages them to understand scientific concepts better (Kurniawan, Mundilarto, and Istiyono 2024).

PBL allows students to relate theory to practice, which is crucial in science learning (Widiawati, Joyoatmojo, and Sudiyanto 2018)-(Towip, Widiastuti, and Budiyanto 2022). As shown in the findings of this study, the PBL model not only improves conceptual understanding but also strengthens students' skills in collaborating and communicating, which are key skills needed in the 21st century (Yanto and Enjoni 2022)- (Saputra, Mahariyanti, and Irwansah 2024). This study also shows that PBL is effective at various levels of education and science materials. From the results of the analysis, it can be seen that the application of PBL at the junior high and high school levels, especially in science learning (biology, physics, chemistry), shows a significant increase (Fitria et al. 2024). This reflects the flexibility of PBL when applied in various science learning contexts. For example, in biology and physics materials, the application of PBL is able to improve students' conceptual understanding and connect scientific concepts with phenomena that occur in real-life (Özer and Kuloğlu 2023)-(Bertel, Kolmos, and Boelt 2021).

Therefore, PBL can be a very useful model for developing science and 21st-century skills at all levels of secondary education (Erasmus, 2020). Although PBL has shown positive results, its implementation also faces a number of challenges. One of the main challenges is the limited time in the learning process, which can affect the effectiveness of PBL, especially if teachers are unable to facilitate group discussions and activities well (Thomassen & Stentoft, 2020)- (Nurul Haritun & Retno Utaminingsih, 2023). In addition, the lack of resources, such as adequate learning materials and limited access to technology, are also obstacles to the optimal implementation of PBL (Tawfik et al., 2021). Therefore, teachers need to design more flexible and creative teaching strategies to overcome these limitations, such as utilising local resources or existing technology to improve the student learning experience (Chian, Bridges, and Lo 2019). In the context of education policy, the results of this study show that the implementation of PBL should be encouraged more widely in schools, especially to improve students' science literacy and 21st-century skills (Syamsinar, Rahman, and Dassa, 2023). Broader application of PBL can strengthen competency-based curricula and develop 21st-century skills among high school students (van Laar et al., 2020).

CONCLUSION

Based on the results of the study, it can be concluded that the Problem-Based Learning (PBL) learning model has a significant role in improving students' science literacy and 21st-century skills. The results of the meta-analysis of the 36 selected articles showed that the application of the Problem-Based Learning (PBL) learning model had a real positive effect, with an average student score of 72.22 and an effect size (ES) of 0.52, which was included in the category of medium effect. These findings show that PBL not only improves students' conceptual understanding of science materials but also strengthens essential skills in the 21st century, such as critical thinking, collaboration, and communication. Although PBL has proven to be effective, its implementation in the classroom is not without challenges. Limited time, resources, and differences in student characteristics are some of the factors that need to be considered so that the implementation of PBL can run optimally. Therefore, stronger support is needed from education policies, including more intensive teacher training and the provision of adequate resources to support the implementation of the Problem-Based Learning (PBL) learning model. Thus, this meta-analysis research makes the Problem-Based Learning (PBL) model an innovative learning model to support educational transformation in developing science literacy and 21st-century skills in high school students.

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