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Meta-Analysis of the Effect of STEM-Integrated Learning Models on Students' Scientific Literacy in Science Education in Indonesia

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Abstract: In the 21st-century education era, scientific literacy has emerged as a crucial competency for addressing global challenges. The integrated STEM (Science, Technology, Engineering, and Mathematics) instructional approach is considered a promising strategy for enhancing students' mastery of scientific literacy through interdisciplinary integration. However, there remains inconsistency in findings regarding the effectiveness of various STEM models, particularly within the Indonesian educational context. This study aims to examine the effectiveness of integrated STEM learning models on students' scientific literacy in Indonesia through a meta-analytic approach. A total of 10 peer-reviewed articles published between 2021 and 2025 were analyzed using the *Comprehensive Meta-Analysis (CMA)* software version 4. The results indicate that STEM-based learning demonstrates a high overall effect size of 0.995 (categorized as large, $p < 0.001$). Among the models examined, Project-Based Learning (PjBL) emerged as the most effective and consistent model, while Problem-Based Learning (PBL) exhibited a relatively smaller effect size. Other models, such as Blended Learning, Inquiry Learning, and RADEC, also showed very high effectiveness; however, these findings require further empirical validation through additional studies. Moderator analysis revealed significant differences across the models ($Qb = 7.85$; $p = 0.005$), suggesting that the type of instructional model moderates the effectiveness of the STEM approach. These findings support the development of more evidence-based and contextually relevant science teaching strategies tailored to the Indonesian educational landscape.

Keywords: Learning models; Meta-analysis; Scientific literacy; STEM

Introduction

In today's era, which is marked by rapid technological advancements and the overwhelming flow of information, developing literacy skills has become a fundamental necessity. These skills equip individuals with the ability to think critically, reason scientifically, and make informed decisions when facing complex life challenges. This aligns with Arifin et al. (2024), who assert that 21st-century individuals are required to master four essential competencies: literacy proficiency, creative thinking skills, effective communication abilities, and high productivity levels.

Scientific literacy plays a pivotal role in fostering critical and innovative thinking, which are essential attributes for navigating the demands of the 21st century (Sanjiartha et al., 2024). Scientific literacy refers to one's ability to understand and apply scientific concepts in everyday life situations (Budianti et al., 2024; Januarti et al., 2024). It encompasses a set of scientific competencies

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that enable individuals to formulate questions, acquire new information, comprehend natural phenomena, and draw conclusions based on factual data (Limiansih et al., 2024; Latifah et al., 2024).

However, the level of scientific literacy among Indonesian students remains a major concern within the national education agenda, given that Indonesia's scores in the Program for International Student Assessment (PISA) have consistently ranked below the OECD average. According to the (OECD, 2023), the results of the 2022 PISA assessment placed Indonesia at 67th out of 81 participating countries, with an average score of 383. Alarmingly, the 2022 science literacy score was even lower than Indonesia's performance in 2006 (Limiansih et al., 2024). The low level of scientific literacy has significant implications: students tend to be less responsive in addressing environmental problems and social changes, struggle to apply scientific knowledge in daily life, face greater difficulties in solving problems, and take longer to make informed decisions (Yusmar & Fadilah, 2023; Doyan et al., 2020; Chalik & Cahyani, 2024). This situation highlights a crisis in science education within schools, which demands serious attention by implementing innovative, contextual, and integrative learning strategies.

Amid the dynamics of the Fourth Industrial Revolution and the accelerating wave of digital transformation, the demand for a scientifically literate workforce and citizenry proficient in science, technology, engineering, and mathematics (STEM) has become increasingly urgent. STEM is an educational approach that integrates science, technology, engineering, and mathematics to create contextual, problem-based learning environments that encourage students to apply their knowledge in real-world situations (Wulandari et al., 2023; Ardiansyah & Asikin, 2023). STEM-based instruction fosters a learning environment where students are encouraged to grow and develop problem-solving skills grounded in all four core STEM domains (Sirait et al., 2023). As a result, the STEM (Science, Technology, Engineering, Mathematics) approach has been globally promoted as a pedagogical framework capable of enhancing scientific literacy and higher-order thinking skills. It emphasizes interdisciplinary integration and the resolution of contextual problems closely related to students' everyday lives (Paramita et al., 2021; Widya et al., 2024).

In Indonesia, the STEM approach has been widely adopted in various science learning experiments at both primary and secondary education levels to enhance scientific literacy. One key strategy for implementing STEM is the integration of appropriate instructional models. This is consistent with the findings of Wahyu et al (2023), who assert that combining Project-Based Learning (PjBL), STEM-based instruction, and relevant local science content creates an effective learning environment for strengthening scientific understanding, critical thinking, and students' problem-solving abilities. The use of teaching materials that integrate STEM and PjBL approaches has been proven to improve students' average scientific literacy. The most significant improvement was observed in students' ability to explain scientific phenomena, which reached 81% and was classified in the high category (Amdayani et al., 2023).

Nevertheless, a review of recent literature reveals that most STEM learning studies conducted in Indonesia are experimental in nature and tend to focus on limited local outputs (Saragih et al., 2025). There remains a lack of systematic efforts to synthesize these findings through a meta-analytic framework that could offer a broader understanding of the effectiveness of STEM approaches on scientific literacy within Indonesia's diverse and dynamic educational context.

Previous studies have conducted meta-analyses related to STEM and scientific literacy. For instance, Supriyadi et al (2023) analyzed the effectiveness of blended learning integrated with STEM on students' scientific literacy in Indonesia. Similarly, Hariyadi et al. (2023) examined the extent to which STEM-based mind mapping models enhance students' scientific literacy in the era of the Fourth Industrial Revolution. However, neither study has yet to explore other instructional models comprehensively. Another study by Tanjung et al. (2022) conducted a meta-analysis on the impact of STEM-based science learning on students' scientific literacy and learning outcomes. Nonetheless, this study only reviewed articles published between 2015 and 2021.

Furthermore, meta-analytic studies are essential to determine, in aggregate, the extent to which various STEM-based instructional models impact students' scientific literacy, particularly in recent research. This is especially important given that the success of STEM approaches largely depends on the quality of implementation and the sociocultural context in which education takes place (Handayani & Nisa, 2025). In addition to addressing this scientific gap, the present meta-analysis is expected to provide an evidence-based foundation for policymakers and educators to design more effective science teaching strategies, particularly in fostering scientific literacy. When systematically designed and evaluated, the STEM approach can serve as a transformative tool in addressing low levels of scientific literacy and preparing Indonesian learners to be globally competitive while remaining locally adaptive (Fatimah et al., 2024).

Therefore, this study's objective is to investigate the influence and effectiveness of STEM-based instructional approaches in enhancing the scientific literacy of Indonesian students through a meta-analytic method.

The findings are anticipated to contribute to the development of more targeted and contextually relevant educational policies and evidence-based instructional practices.

Method

This study employs a meta-analytic approach—a systematic method used to integrate and analyze findings from various prior studies focusing on applying the STEM approach in science education and efforts to enhance scientific literacy through instructional model integration. Meta-analysis is a research methodology that evaluates and synthesizes findings from multiple previous studies that contain quantitative data and can be statistically analyzed (Chen et al., 2022). The article selection process adhered to the PRISMA 2020 protocol (Page et al., 2021), ensuring transparency and accountability in the literature search process, as illustrated in Figure 1.

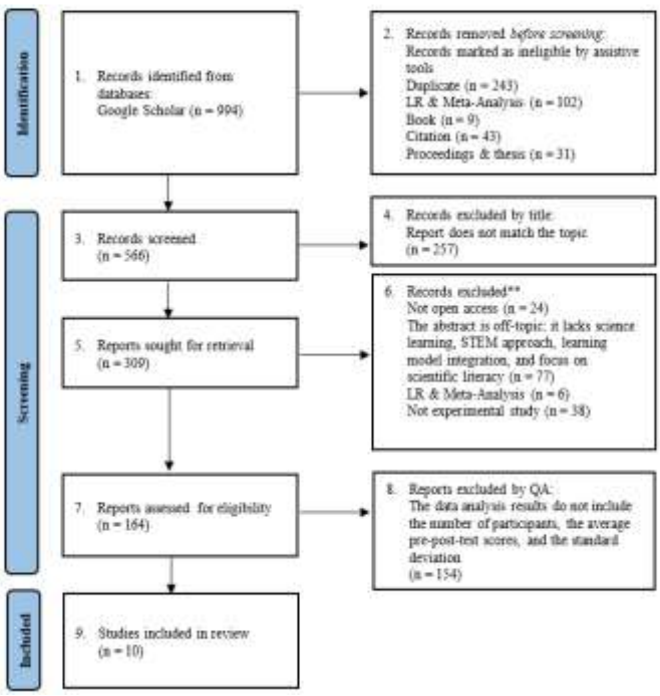

Figure 1. Result of article search using PRISMA 2020

The procedure began with the identification stage by collecting articles through Google Scholar using the Publish or Perish (PoP) application, combined with Boolean keyword searches: ("STEM education" OR "STEM-based learning") AND ("literasi sains" OR "scientific literacy") AND (effectiveness OR impact OR evaluation OR outcome).

The next stage involved screening the articles based on inclusion and exclusion criteria formulated using the PICOS framework (Population, Intervention, Comparison, Outcome, Study type) to ensure a focused and high-quality selection. The Population includes elementary, junior high, and senior high school students involved in science learning; the Intervention refers to instructional models integrated with the STEM approach; the Comparison involves conventional science instruction or non-STEM learning models; the Outcome is measured by improvements in scientific literacy; and the Study type is limited to quantitative research employing experimental, quasi-experimental, or pre-experimental methods, which report participant numbers, means, and standard deviations. The publication period of journal articles is limited to 2021–2025, in either Indonesian or English.

The subsequent stage is article analysis. This stage consists of several steps, beginning with calculating the effect size of each article using the Comprehensive Meta-Analysis (CMA) software version 4. The calculated effect sizes are then categorized according to Cohen's effect size classification (Cohen, 1998), as presented in Table 1.

Table 1. Cohen's Effect Size Classification

Effect Size (ES)	Category
$0.00 \leq ES < 0.20$	Ignored
$0.20 \leq ES < 0.50$	Small
$0.50 \leq ES < 0.80$	Moderate
$0.80 \leq ES < 1.30$	Large
$1.30 \leq ES$	Very large

Second, bias analysis was conducted to assess the potential for publication bias. This was examined using a funnel plot, while plot asymmetry was evaluated through Egger's regression test. A p-value of less than 0.1 in the funnel plot was considered to indicate significant asymmetry. Third, heterogeneity testing was performed. Clinical heterogeneity was assessed using the Chi-square test and the I^2 index to determine the degree of variation across studies. A fixed-effects model was applied if the results indicated homogeneity ($I^2 < 50\%$ and $p > 0.1$). Conversely, if heterogeneity was present ($I^2 \geq 50\%$ and $p < 0.1$), a random-effects model was used for analysis. The data were analyzed and presented as Standardized Mean Differences (SMD) with a 95% Confidence Interval (95% CI). The final stage involved interpreting the data by reviewing the overall results. A p-value less than 0.05 was interpreted as a statistically significant difference between groups.

Result and Discussion

Ten articles that met the predetermined inclusion criteria were identified based on the results of journal article searches conducted using the Publish or Perish application through the Google Scholar database. The next stage involves conducting a complete analysis of these 10 articles using the meta-analytic research method to obtain statistical findings. The details of the articles selected for the study are presented in Table 2.

Table 2. Article Identity

Code	Author	Method
A1	(Susilo et al., 2021)	Experimental
A2	(Usemahu et al., 2022)	Quasi-Experimental
A3	(Nurhayati et al., 2023)	Experimental
A4	(Putri et al., 2023)	Experimental
A5	(Sholihah et al., 2023)	Quasi-Experimental
A6	(Hanim et al., 2023)	Quasi-Experimental
A7	(Silfiyani et al., 2024)	Experimental
A8	(Pertiwi et al., 2024)	Experimental
A9	(Nuraisyah et al., 2025)	Experimental
A10	(Tairas et al., 2025)	Experimental

Subsequently, data from all selected studies were analyzed by extracting statistical information and relevant study characteristics. The results of this extraction process were organized and presented in Table 3. In the conducted meta-analysis, the initial stage involved determining the effect size of each study. The calculated effect sizes and their corresponding categories for each study are presented in Table 4.

Based on Table 4, the percentage distribution of effect sizes across the articles can be interpreted as follows: Articles coded A2, A4, A5, and A6 fall into the very large effect size category, representing 40% of the total. Articles A7 and A8 are categorized as having a large effect size, accounting for 20%. In the moderate category, there are three articles—A1, A3, and A9—constituting 30%. Meanwhile, Article A10 falls under the lowest effect size category, with a percentage of 10%.

In this study, the highest effect size was recorded in Article A6, with a value of 2.445, while the lowest effect size was found in Article A10, with a value of 0.237.

Table 3. Summary of Statistical Data Extraction Results

Code Article	Statistical Data						Learning Model
	Control Group			Experimental Group			
	Mean	SD	N	Mean	SD	N	
A1	62.30	8.82	30	68.67	8.79	30	Project Based Learning
A2	59.72	14.78	36	85.52	7.35	36	Blended Learning
A3	78.35	5.42	20	82.30	6.71	20	Project Based Learning
A4	78.00	7.95	24	88.00	6.85	24	RADEC
A5	82.00	6.63	30	83.04	6.29	28	Problem Based Learning
A6	29.17	13.79	12	81.67	25.88	12	Inquiry
A7	64.79	12.96	64	79.74	12.98	64	Project Based Learning
A8	82.22	7.14	36	88.6	2.95	35	Project Based Learning
A9	78.83	6.18	30	82.53	7.15	30	Problem Based Learning
A10	0.477	0.251	57	0.543	0.301	57	Problem Based Learning

Table 4. Meta-Analysis Effect Size of Each Article

Article Code	Effect Size (Hedges'g)	Category	Confidence Interval		Standard Error
			Lower Limit	Upper Limit	
A1	0.714	Moderate	0.198	1.230	0.263
A2	2.187	Very large	1.607	2.767	0.296
A3	0.635	Moderate	0.012	1.258	0.318
A4	1.326	Very large	0.709	1.942	0.315
A5	0.159	Very large	-0.350	0.668	0.260
A6	2.445	Very large	1.408	3.481	0.529
A7	1.146	Large	0.774	1.518	0.190
A8	1.149	Large	0.625	1.647	0.254
A9	0.546	Moderate	0.038	1.055	0.260
A10	0.237	Small	-0.129	0.603	0.187

The next stage involved testing the reliability of the effect size data through publication bias analysis. The distribution of effect sizes for this analysis is illustrated in the funnel plot shown in Figure 2.

Based on Figure 2, the distribution of data points is mostly concentrated around the vertical line indicating the mean effect size, forming a funnel-shaped pattern that suggests consistency of results across studies. However, there is a slight visual imbalance, as not all points are symmetrically distributed on both sides of the central line particularly with a denser concentration on the left side. Although no extreme outliers fall far outside the funnel boundaries, this asymmetry may indicate a potential presence of mild publication bias. To confirm this observation, additional statistical tests, such as Egger's regression test or fail-safe N calculation are needed to validate the presence of publication bias.

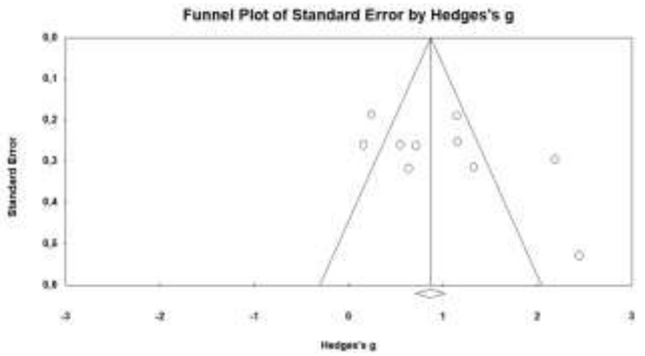

Figure 2. Funnel plot publication bias tests

To further investigate the potential publication bias suggested by the funnel plot, a follow-up analysis was conducted using Egger's regression test and Fail-Safe N (FSN) calculation via the Comprehensive Meta-Analysis (CMA) software version 4. The results of Egger's regression test are presented in Table 5.

Table 5. Results of the Egger'r Regression Tests

Egger'r Regression Intercept	
Intercept	4.78797
Standard error	2.91453
95% lower limit (2-tailed)	-1.93295
95% upper limit (2-tailed)	11.50888
t-value	1.64279
df	8.00000
P-value (1-tailed)	0.06953
P-value (2-tailed)	0.13905

Based on the output of Egger's regression test, the one-tailed p-value was 0.06953, which is greater than the significance threshold of 0.05. This indicates that there is no strong statistical evidence of publication bias. Therefore, the funnel plot can be considered sufficiently symmetrical, suggesting that the meta-analysis results are relatively free from significant publication bias. This finding is further supported by the results of the fail-safe N test, as presented in Table 6.

The results of the Fail-Safe N test, as shown in Table 6, indicate that 318 additional studies with null results would be required to nullify the significance of this meta-analysis. This number far exceeds the 10 studies included in the analysis, suggesting that the meta-analytic findings are stable and unlikely to be affected by publication bias. The next stage of data analysis involved testing for heterogeneity and applying an estimation model to determine the overall effect size of the study. The results of the heterogeneity test are presented in Table 7.

Table 6. Results of the Fail-Safe N Tests

Classic Fail-Safe N	
Z-value for observed studies	11.22093
P-value for observed studies	0.00000
Alpha	0.05000
Tails	2.00000
Z for alpha	1.95996
Number of observed studies	10.00000
Number of missing studies that would bring p-value to > alpha	318.00000

Table 7. Results of the Heterogeneity Tests

Heterogeneity Tests			
Q-value	df (Q)	P-Value	I-squared
55,537	9	0.000	83.795

Based on Table 7, the results of the heterogeneity test indicate a Q-value of 55.537 with 9 degrees of freedom (df) and a p-value of 0.000. A p-value less than 0.05 suggests that there are significant differences in effect sizes across the studies analyzed. This means that the integration of the STEM approach through instructional models has a statistically significant influence on scientific literacy. Furthermore, the I^2 value of 83.795% indicates that approximately 83.79% of the variability is due to true heterogeneity rather than random error. According to the standard interpretation of I^2 values, this result falls into the category of very high heterogeneity. Therefore, these findings suggest that the random-effects model is more appropriate for calculating the overall effect size in this meta-analysis. The results of the effect size analysis using the random-effects model are presented in Table 8.

Table 8. Effect Size Results Based on the Random-effects Model

Estimation Model	N	Z-Value	P-Value	Effect Size	Standard Error	95% Confidence Interval	
						Lower Limit	Upper Limit
Random Effect	10	4.775	0.000	0.995	0.208	0.587	1.404

Based on the random-effects model, the effect size was found to be 0.995 with a standard error of 0.208 and a 95% confidence interval ranging from 0.587 to 1.404. The Z-value was 4.775 with a p-value of 0.000, indicating that the result is statistically significant ($p < 0.05$). According to Cohen's classification, an effect size of 0.995 falls within the large category, suggesting that STEM-integrated instructional models have a strong positive influence on improving students' scientific literacy. The confidence interval, which does not include zero, further reinforces the reliability and significance of this effect. Given the previously identified high level of heterogeneity among the studies (I^2 = 83.8%), the use of the random-effects model is considered the most appropriate approach for estimating the overall effect. Thus, these findings demonstrate that the implementation of the STEM approach consistently yields positive impacts on scientific literacy across various study contexts. Furthermore, to examine the extent to which each STEM-integrated instructional model contributes to this effect, a more detailed analysis is presented in Table 9.

Table 9. Results of the Test on Instructional Model Characteristics

Characteristics	Category	N	Effect Size	Test of Null		Heterogeneity		
				Z	P-value	Qb	df (Q)	P-value
Learning Models	PjBL	4	0.976	5,130	0.000	7.85	1	0.005
	PBL	3	0.293	1,334	0.182			
	RADEC	1	1.326	-	-			
	Blended	1	2.187	-	-			
	Inquiry	1	2.445	-	-			

Based on Table 9, the analysis of the types of STEM-integrated instructional models and their influence on students' scientific literacy reveals that each model applied in the reviewed studies had a different impact on student learning outcomes. The Project-Based Learning (PjBL) model demonstrated an effect size of 0.976, which falls into the high to very high category according to Cohen (1998) classification. This value was also statistically significant ($p < 0.05$), indicating that the PjBL model consistently contributes to a substantial improvement in student learning outcomes. The strength of PjBL lies in its emphasis on real-world projects, which promotes active engagement, problem-solving, and the integration of 21st-century skills elements that align well with the core principles of the STEM approach (Susilo et al., 2021; Nurhayati et al., 2023; Silfiyani et al., 2024; Pertiwi et al., 2024).

In contrast, the Problem-Based Learning (PBL) model showed a relatively low effectiveness, with an effect size of 0.293, which falls within the low to moderate range based on Cohen's (1998) criteria. Moreover, this value was not statistically significant, suggesting that the influence of PBL on students' scientific literacy cannot yet be considered firm or consistent. This outcome may be attributed to the implementation challenges of PBL, which often require a high level of learner autonomy and advanced thinking skills conditions that may not be present among all students (Sholihah et al., 2023; Tairas et al., 2025; Nuraisyah et al., 2025).

Furthermore, the remaining three models, Blended Learning, Inquiry Learning, and RADEC, were each represented by only one study yet demonstrated exceptionally high effect sizes. Blended Learning recorded an effect size of 2.187, Inquiry Learning 2.445, and RADEC 1.326. These effect sizes suggest that all three models hold significant potential for enhancing scientific literacy. However, since each model is supported by only a single study, these interpretations should be considered preliminary. More empirical evidence is needed to strengthen and generalize these conclusions.

Overall, based on the interpretation of the instructional model as a moderator variable, the test of differences in effectiveness between the various instructional models revealed a statistically significant difference, as indicated by the Q-between value of 7.85 with a p-value of 0.005 ($p < 0.05$). This result confirms that the type of instructional model implemented significantly influences the variation in the effectiveness of the STEM approach. This finding highlights the importance of selecting the appropriate instructional model as a critical factor in determining the success of STEM-based learning, particularly in improving students' scientific literacy. This finding highlights the importance of selecting the appropriate instructional model as a critical factor in determining the success of STEM-based learning, particularly in improving students' scientific literacy.

The results of this meta-analysis indicate that STEM-integrated instructional models generally have a large and statistically significant effect on improving students' scientific literacy, particularly in the Indonesian context, as evidenced by an effect size of 0.995 (categorized as high). This finding aligns with the studies of Paramita et al. (2021) and Widya et al. (2024), which confirmed that STEM-based learning can enhance students' conceptual understanding and scientific thinking skills. The Project-Based Learning (PjBL) model demonstrated the most consistent and significant impact ($g = 0.976$), which is attributed to its ability to foster active engagement and contextual problem-solving. Conversely, the Problem-Based Learning (PBL) model yielded a lower and statistically insignificant effect size ($g = 0.293$), likely due to implementation challenges, especially regarding students' readiness and autonomy.

On the other hand, three different models in this study, Blended Learning, Inquiry Learning, and RADEC, reported very high effect sizes. However, since each was represented by only one study, the generalizability of these findings remains limited.

Nevertheless, the substantial potential of these models should not be overlooked. The test of heterogeneity across instructional models (Q-between = 7.85; p = 0.005) revealed a significant difference in the level of effectiveness among the various models, suggesting that the choice of instructional model plays a critical role in determining the success of STEM integration in enhancing scientific literacy. These findings support the view of Fatimah et al. (2024), who emphasized that a systematically and contextually designed STEM pedagogical framework can serve as a transformative instrument for improving the quality of science education in Indonesia, particularly in advancing scientific literacy.

Conclusion

Based on the meta-analysis of 10 articles that met the inclusion criteria, instructional models integrated with the STEM approach have a large and statistically significant impact on students' scientific literacy. This is evidenced by an overall effect size of 0.995, indicating the high effectiveness of this approach. Among the models examined, Project-Based Learning (PjBL) was found to be the most effective and consistent. In contrast, other models, such as Blended Learning, Inquiry Learning, and RADEC, also demonstrated strong potential. However, these latter models require further empirical support through additional studies to confirm their effectiveness. The findings of this meta-analysis emphasize that the effectiveness of the STEM approach is highly influenced by the instructional model employed. This underscores the importance of contextual and problem-based instructional design to improve scientific literacy comprehensively. Further research is needed to examine the effectiveness of STEM-integrated instructional models across various educational levels and diverse learning contexts, particularly for models like Blended Learning, Inquiry Learning, and RADEC, which currently have limited empirical evidence.

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I.K.A was responsible for article retrieval, data analysis, manuscript writing, and submission for publication. I.W.R. and I.N.T. contributed to the review and editing process of the manuscript to ensure academic quality and the relevance of the content.

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Conflicts of Interest
The author declares that there are no conflicts of interest, either financial or non-financial, that influenced the conduct or outcomes of this study.

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