



# The Effect of the STEM-Based 5E Learning Cycle Model on Science Literacy and Learning Outcomes of Elementary Teacher Education Students

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Received: November 26, 2025

Revised: December 23, 2025

Accepted: January 25, 2026

Published: January 31, 2026

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DOI: [10.29303/jppipa.v12i1.13617](https://doi.org/10.29303/jppipa.v12i1.13617)

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**Abstract:** This study examines the effect of the STEM-based 5E Learning Cycle model on science literacy and learning outcomes of preservice elementary teachers. A quasi-experimental one-group pretest-posttest design was employed involving 29 first-semester students in an Elementary Teacher Education program. The intervention was implemented through STEM-integrated learning activities using hydraulic media across the five phases of the 5E learning cycle. Data were analyzed using descriptive statistics, the Shapiro–Wilk normality test, the Wilcoxon signed-rank test, normalized gain (N-gain), and effect size analysis. The results showed a significant improvement in students' science literacy, with mean scores increasing from 63.45 to 91.72 ( $p < 0.001$ ). The average N-gain value of 0.7817 indicated a high level of learning improvement, while the effect size analysis revealed a very large effect (Cohen's  $d = 2.619$ ). Qualitative findings supported the quantitative results, indicating that hands-on inquiry, structured exploration, and contextual STEM tasks enhanced students' conceptual understanding and scientific reasoning. In conclusion, the STEM-based 5E Learning Cycle model is effective in improving science literacy and learning outcomes among preservice elementary teachers and holds strong potential for broader application in teacher education.

**Keywords:** 5E learning cycle; Learning outcomes; Science literacy; STEM

## Introduction

The development of information and communication technology has generated substantial changes in the field of education over the past two decades. Higher education institutions are now required to integrate technology into learning processes to align with the demands of the twenty-first century and advancements in the digital era (Wiriani & Ardana, 2022; Kelana et al., 2020; Lestari et al., 2025). This transformation compels students to adapt to more interactive and technology-mediated learning environments that support the improvement of scientific literacy skills (Mananghaya et al., 2024).

The rapid development of information and communication technology has significantly transformed educational practices over the past two decades. Higher education institutions are increasingly required to integrate technology into learning processes to meet the demands of the twenty-first century and the digital era (Mananghaya et al., 2024; Muliyadi et al., 2023; Ernest & Suyanta, 2024; Nurbaya et al., 2025).

This transformation compels students to adapt to more interactive and technology-mediated learning environments that support the development of scientific literacy skills (Hernández-Ramos et al., 2021). Furthermore, the shifts driven by the Industrial Revolution 4.0 and Society 5.0 require educational

### How to Cite:

Nazara, R. G., Firdaus, F. M., Sayekti, O. M., Hidayat, P., Fatimah, W. S., & Adiningsih, Z. D. (2026). The Effect of the STEM-Based 5E Learning Cycle Model on Science Literacy and Learning Outcomes of Elementary Teacher Education Students. *Jurnal Penelitian Pendidikan IPA*, 12(1), 282–291. <https://doi.org/10.29303/jppipa.v12i1.13617>

institutions to continuously respond to technological advancements, not only in instructional systems but also in the competencies expected of learners (Adel, 2024), including critical, creative, collaborative, and communicative skills (Rochmawati, 2023; Handayani et al., 2024).

The shifts driven by the Industrial Revolution 4.0 and Society 5.0 have compelled higher education institutions to innovate curriculum and instructional practices to cultivate critical, creative, collaborative, and communicative skills among learners. Research indicates that higher education must adapt quality parameters and strategic directions to respond to these technological demands (Rochmawati, 2023; Yuyung et al., 2024).

Globally, the 2022 Programme for International Student Assessment (PISA) results indicate that Indonesia’s performance in science remains below international benchmarks, reflecting limited mastery of scientific concepts in everyday contexts. Indonesia achieved an average science score of 383 points, far below the OECD average of 489 points (OECD, 2019). This gap highlights students’ insufficient ability to understand, interpret, and apply scientific knowledge in real-life situations (Pratama et al., 2025). Such findings reinforce the urgency of implementing instructional strategies that strengthen conceptual understanding and promote scientific reasoning skills.

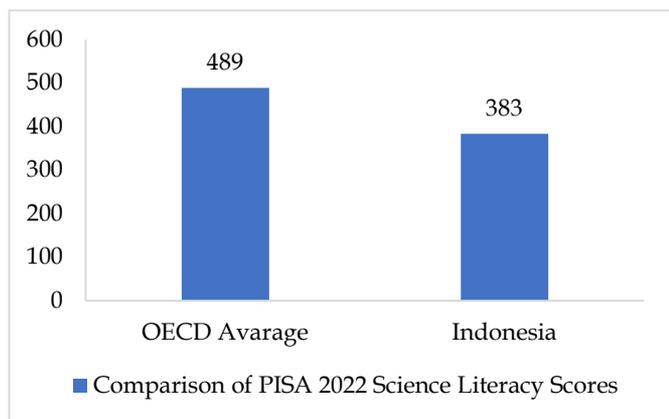


Figure 1. Comparison of PISA 2022 science literacy scores

Based on Figure 1, This condition is not limited to secondary education but extends to higher education. First-year university students, particularly those transitioning directly from senior high school, often demonstrate low scientific literacy, difficulty connecting theoretical concepts to real-world phenomena, and limited engagement in rigorous scientific inquiry (Batubara et al., 2025; Pranata et al., 2023; Nilyani et al., 2023). These challenges are particularly evident among students enrolled in Elementary Teacher Education programs, who frequently rely on rote memorization

and teacher-centered learning practices (Sukardiyono et al., 2025). Preliminary observations of 29 first-semester students in the Elementary Teacher Education Program at Universitas Ahmad Dahlan revealed that most students were not yet accustomed to exploratory and inquiry-based learning approaches (Ristiani et al., 2025).

This phenomenon also persists at the higher education level. First-year university students, particularly those enrolled in Elementary Teacher Education programs, often struggle to comprehend scientific concepts and relate them to real instructional applications. Preliminary observations of 29 first-semester students in the Elementary Teacher Education Program at Universitas Ahmad Dahlan revealed that most students still rely heavily on memorization and are not yet accustomed to engaging in exploratory scientific approaches.

This situation aligns with previous studies reporting that preservice teachers in Indonesia exhibit low levels of scientific literacy due to the dominance of conventional instructional practices that emphasize information transmission rather than conceptual understanding (Allanta & Puspita, 2021; Safitri et al., 2024).

The limited scientific literacy of preservice elementary teachers represents a critical concern, as these individuals will be responsible for introducing scientific concepts and inquiry skills to young learners (Strat et al., 2024). When future teachers themselves lack deep scientific understanding, improving the quality of science instruction at the elementary level becomes increasingly difficult (Wu et al., 2022; Ningthias & Rahayu, 2025). Therefore, instructional innovations that foster scientific reasoning, conceptual mastery, and inquiry skills among preservice teachers are urgently needed (Pratama et al., 2025).

One instructional approach that holds strong potential to address these challenges is the integration of the STEM approach with the 5E Learning Cycle model. The 5E Learning Cycle with consisting of Engage, Explore, Explain, Elaborate, and Evaluate phases (Ünlü & Dökme, 2022). Provides a structured inquiry framework that supports active engagement, concept construction, contextual problem-solving, and reflective evaluation (Bybee et al., 2006). When combined with STEM, this model enables learners to connect scientific concepts with technological applications, engineering design, and mathematical reasoning through hands-on and contextual learning experiences (Sulaiman et al., 2024; Sinaga et al., 2025).

Although previous studies have demonstrated the effectiveness of STEM-based learning and the 5E Learning Cycle in improving learning outcomes, scientific creativity, and conceptual understanding (Agustina et al., 2021), most of this research has been

conducted at the elementary and secondary school levels (Khumairoh et al., 2025; Nurussalma et al., 2024; Umami & Wulandari, 2025). Moreover, many studies examine STEM and inquiry-based learning separately, without integrating STEM systematically within the complete 5E instructional sequence (Kruatong et al., 2022; Lestaria et al., 2021). Empirical evidence investigating the combined implementation of a STEM-oriented 5E Learning Cycle in higher education, particularly within preservice elementary teacher education, remains limited (Umami & Wulandari, 2025).

The novelty of this study lies in its explicit integration of the STEM approach within the full 5E Learning Cycle framework and its application in the context of preservice elementary teacher education (Gilbert et al., 2025). Unlike prior research that focuses primarily on school students or examines STEM or inquiry-based models independently (Wiriani & Ardana, 2022; Cahyani et al., 2021), this study provides empirical evidence on how the STEM-based 5E Learning Cycle simultaneously enhances scientific literacy and learning outcomes among future elementary teachers (Nisa et al., 2024). In addition, this research conceptualizes scientific literacy as a multidimensional construct encompassing conceptual understanding, evidence-based reasoning, data interpretation, and the application of scientific knowledge in technological and engineering contexts, an aspect that has rarely been examined comprehensively in teacher education research (Valladares, 2021).

This study is important for several reasons. First, improving scientific literacy among preservice elementary teachers constitutes a long-term investment in the quality of science education at the primary level. Second, the STEM-based 5E Learning Cycle offers a pedagogically grounded and practically applicable instructional model that aligns with the competency demands of the digital era and Society 5.0. Third, evidence derived from higher education contexts is essential for informing curriculum design and instructional practices in teacher education programs, which are expected to prepare graduates with strong scientific understanding and effective pedagogical skills (Parmin et al., 2023; Luah et al., 2025; Firman et al., 2025).

Therefore, this study aims to examine the effect of the STEM-based 5E Learning Cycle model on scientific literacy and learning outcomes of preservice elementary teachers. The findings are expected to contribute theoretically to the literature on STEM and inquiry-based learning in higher education and practically to the development of effective instructional strategies for strengthening scientific literacy in elementary teacher education programs.

## Method

This study was conducted in the Elementary Teacher Education Program at Universitas Ahmad Dahlan during the odd semester of the 2025/2026 academic year. A quasi-experimental methodology was applied, employing a one-group pretest-posttest design to rigorously assess the influence of the STEM-based 5E Learning Cycle on the scientific literacy competencies of preservice elementary teachers. The selection of this design was grounded in its suitability for measuring changes in learning outcomes before and after the implementation of a specific instructional intervention.

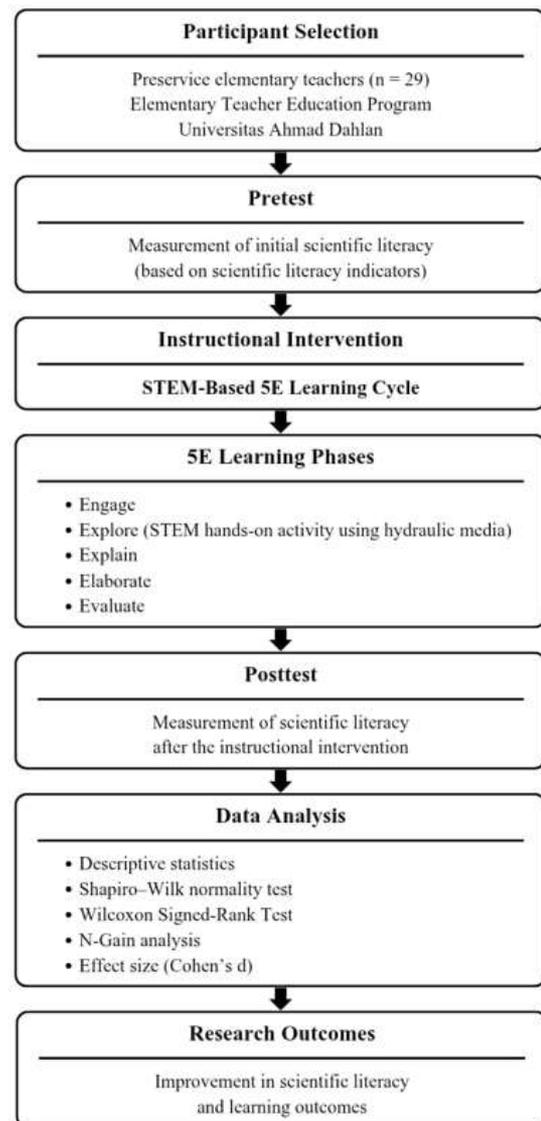


Figure 2. Research flow of STEM-5E learning cycle

The study involved 29 first-semester students enrolled in the Elementary Teacher Education Program. Participants were identified through purposive sampling, based on the academic relevance of their enrollment in the Fundamental Science course, which

aligns with the conceptual demands of the STEM-integrated 5E instructional model. The procedural structure of the one-group pretest–posttest design utilized in this research is outlined as follows:

**Table 1.** Distribution of Data for the Experiment

Group	Pretest	Treatment	Posttest
Experiment	O <sub>1</sub>	X	O <sub>2</sub>

Description:

O<sub>1</sub> = Pretest measuring students’ scientific literacy

X = Treatment using the STEM-based 5E Learning Cycle model

O<sub>2</sub> = Posttest measuring students’ scientific literacy

The data analysis procedure encompassed both descriptive and inferential statistical approaches. Prior to conducting hypothesis testing, the normality of the dataset was evaluated using the Shapiro–Wilk test, which was deemed appropriate given the sample size of

fewer than 50 participants and its higher sensitivity in identifying distribution characteristics. When the distribution met the assumption of normality, the difference between pretest and posttest scores was examined using the Paired Sample t-test. In cases where the normality assumption was not satisfied, the Wilcoxon Signed Rank Test served as the nonparametric alternative. Furthermore, enhancements in students’ scientific literacy were assessed using the normalized gain (N-gain) metric, calculated according to the established formula. The criteria for interpreting N-gain values are presented in Table 2

**Table 2.** N-Gain score for each Indicator (Lestari et al., 2018)

N-gain score	Category
$g < 0.3$	Low
$0.3 \leq g < 0.7$	Middle
$g \geq 0.7$	High

**Table 3.** Science Literacy Competency Indicators (OECD, 2019)

Science Literacy Indicators	Description
Understanding Scientific Concepts	Explaining core scientific concepts accurately and coherently (e.g., fluid pressure, Pascal’s Law, force–area relationships).
Using Evidence to Explain Phenomena	Providing scientific explanations based on observations, experimental data, or evidence-based arguments.
Concept-Based Problem Solving	Applying scientific concepts to solve real-world problems, such as hydraulic systems, technological tools, or everyday scientific events.
Interpreting Data and Scientific Representations	Reading, interpreting, and using tables, graphs, diagrams, or comparative representations to explain scientific phenomena.
Applying Scientific Knowledge in Technological and Engineering Contexts	Connecting scientific concepts to the use of technology, tool design, prototype modification, and understanding the function of devices in daily life.

In Table 3 above, qualitative data were collected to explore students’ perceptions, experiences, and challenges during the implementation of the STEM–5E model. The instruments used consisted of a questionnaire containing 20 statements related to scientific literacy and STEM, as well as a semi-structured interview guide comprising five core questions addressing learning experiences, perceived ease and difficulty, students’ views on the steps of the 5E Learning Cycle, and the relevance of the learning process to the STEM context.

The scientific literacy instrument used in this study was developed based on five key indicators of scientific literacy, namely: understanding scientific concepts, using evidence to explain phenomena, concept-based problem solving, interpreting data and scientific representations, and applying scientific knowledge in technological and engineering contexts.

The indicator of data interpretation and scientific representation assesses students’ ability to read, interpret, and utilize tables, graphs, or diagrams to explain scientific phenomena. Meanwhile, the indicator of applying scientific knowledge in technological and

engineering contexts measures the extent to which students can connect scientific concepts with the use of simple technologies, the design of tools, or prototype modifications relevant to everyday life. This instrument was used to comprehensively assess students’ scientific literacy abilities within the context of learning based on the STEM approach and the 5E Learning Cycle model. Qualitative data were obtained from students’ learning experiences to examine their perceptions, experiences, and challenges encountered during the implementation of the STEM–5E learning model.

The analysis procedure was conducted sequentially, beginning with quantitative descriptive statistical analysis using JASP version 0.18.3 and SPSS version 25. The subsequent stage involved thematic analysis of the qualitative data to identify patterns of meaning, emerging tendencies, and their connection to the quantitative findings, thereby enabling a more comprehensive and in-depth interpretation (Ivankova et al., 2006; Waruwu, 2023).

## Result and Discussion

### Hydraulic Learning Media

The learning media used in this study consisted of a simple hydraulic teaching aid assembled using syringes, flexible tubing, and a cardboard vehicle prototype. This media was implemented during the Explore and Elaborate phases of the STEM-based 5E Learning Cycle, where students were required to investigate the principles of fluid pressure through direct laboratory activities.

The implementation of this media, as shown in Figure 2, illustrates students collaboratively operating the hydraulic system and analyzing the resulting motion. These activities were designed to enhance students' scientific literacy while simultaneously strengthening their conceptual understanding through authentic and STEM-oriented learning experiences.

Furthermore, these learning activities were intentionally designed to enhance students' scientific literacy while simultaneously strengthening their conceptual understanding through authentic and STEM-oriented learning experiences. By integrating science concepts with engineering design and problem-solving tasks, students were able to connect theoretical knowledge with real-world applications. As a result, the use of simple hydraulic learning media within the STEM-based 5E Learning Cycle contributed to deeper conceptual comprehension and improved scientific literacy among preservice elementary teachers.



Figure 3. Students conducting a hydraulic pressure test

### Students' Learning Outcomes

The normality of data normality in this study employed the Shapiro-Wilk test. Within this test, a p-value greater than 0.05 signifies that the dataset meets the assumption of normality, while a value below 0.05 reflects a non-normal distribution. The normality analysis conducted to evaluate the influence of the STEM-based 5E Learning Cycle on students' scientific literacy and learning outcomes is summarized in Table 4.

Table 4. Summary of Descriptive Statistics

Descriptive Statistics	Pretest	Posttest
Valid	29	29
Missing	0	0
Mean	63.448	91.724
Std. Deviation	13.236	5.867
Shapiro-Wilk	0.945	0.846
P-value of Shapiro-Wilk	0.14	< .001
Minimum	30	75
Maximum	85	100

The summary of descriptive statistics in Table 4 indicates a clear contrast between students' scores before and after the intervention. Prior to the learning treatment, students obtained an average score of 63.45 with a standard deviation of 13.24. After the treatment, the mean score rose markedly to 91.72, accompanied by a smaller standard deviation of 5.87. The distribution of scores at the pretest stage extended from 30 to 85, while the posttest scores were concentrated between 75 and 100. When the Shapiro-Wilk procedure was applied to examine data normality, the pretest values met the criterion for normal distribution ( $p = 0.140$ ). In contrast, the posttest values yielded a significance level below 0.001, indicating that these data did not satisfy the assumption of normality.

Interpretatively, the increase in the mean score from 63.45 to 91.72, accompanied by a substantial reduction in standard deviation (from 13.24 to 5.87), indicates that most participants achieved considerably higher scores after the intervention and that their performance became more consistent, as shown by the decreased variability among students. In other words, overall performance improved and became more homogeneous following the treatment, despite the posttest distribution not meeting normality assumptions.

The normality assessment presented in Table 4 shows that the pretest data met the required assumption, as reflected by a Shapiro-Wilk p-value of 0.140, which exceeds the 0.05 threshold. Conversely, the posttest data produced a significance value below 0.001, indicating that these scores were not normally distributed. Since the posttest dataset violated the normality criterion, the comparison between the two sets of scores could not be carried out using the parametric paired t-test. As a result, the appropriate procedure for examining the change in performance is the Wilcoxon Signed-Rank Test, which does not rely on the assumption of normality.

Table 5. Results of the Paired Samples Test

Measure 1	Measure 2	Paired Samples T-Test			
		Test Statistic	z	df	p
Pretest	Posttest	Student	-14.104	28	0.001
		Wilcoxon	0	-4.703	0.001

Table 5 shows that the statistical comparison between the pretest and posttest scores reveals a clear shift in students' performance. The Paired t-test conducted on the data produced a value of  $t = -14.104$  with 28 degrees of freedom and a significance level below 0.001, indicating a marked rise in achievement after the learning intervention. Since the posttest distribution violated the normality requirement based on the Shapiro-Wilk test, further interpretation was guided by the nonparametric procedure. The Wilcoxon Signed-Rank Test yielded  $W = 0.000$  and  $z = -4.703$  with a p-value below 0.001, which reinforces that the difference between the two sets of scores was substantial. Taking together, the outcomes of both tests confirm that the instructional treatment brought about a meaningful improvement in student learning.

The magnitude of this improvement is further reflected in the substantial increase in the mean scores, rising from 63.448 on the pretest to 91.724 on the posttest, as shown in the preceding table. Overall, these results affirm that the learning treatment applied in this study effectively elevated student performance in a statistically significant manner. A subsequent analysis was conducted to calculate the N-Gain score to measure the degree of improvement in a more standardized form.

**Table 6.** Summary of Descriptive N-gain Score

Descriptive	N	Min	Max	Mean
N-gain_percent	29	0.50	1.00	0.7817
N-gain score	29	50.00	100.00	78.1687
Valid N (listwise)	29			

Based on the descriptive analysis, the n-gain percent for the 29 participants showed an average value of 0.7817, with a range from 0.50 to 1.00. This average falls within the high category, indicating that the improvement in students' abilities following the learning intervention reached an optimal level. Furthermore, the n-gain score recorded an average of 78.17, with a minimum value of 50.00 and a maximum of 100.00. The relatively homogeneous distribution within the medium to high categories demonstrates that the increase in learning outcomes occurred consistently across all participants.

These findings reinforce that the implementation of the STEM-based 5E Learning Cycle model produced a significant positive effect on students' conceptual understanding. To further strengthen the interpretation of the magnitude of this effect, an effect size analysis using Cohen's d was conducted, as presented in Table 7.

Based on the data presented in Table 7, the Cohen's d value of  $-2.619$  indicates a very large effect size. In practical terms, the magnitude of this absolute value suggests that the improvement observed is not only statistically significant but also pedagogically

meaningful. The average increase of 28.27 points in scientific literacy reflects a substantial and stable shift in performance across nearly all students. This interpretation is further supported by the 95% confidence interval, which lies far from zero, indicating the consistency and reliability of the estimated effect. In the context of elementary teacher education, these findings demonstrate that the STEM-5E model not only strengthens conceptual understanding but also produces a significant enhancement in the competency levels of preservice elementary school teachers.

**Table 7.** Effect Size Analysis Using Cohen's d

Paired Samples T-Test				
Measure 1	Measure 2	t	Cohen's d	SE Cohen's d
Pretest	Posttest	-14.104	-2.619	0.35

In addition, the standard error of Cohen's d, which was 0.350, together with the 95% confidence interval ranging from  $-3.387$  to  $-1.840$ , further strengthens the consistency of the treatment effect across a broader population. The fact that the entire interval lies well below zero confirms that the post-treatment improvement genuinely occurred and reflects a stable and substantial effect size.

The significant increase in participants' abilities following the intervention indicates that structured inquiry and opportunities for independent exploration played a critical role in fostering conceptual understanding. Rahmawati et al. (2021) highlight that the exploration phase within the 5E model effectively nurtures curiosity, enhances learner interaction, and helps students link their prior experiences to new scientific concepts. Furthermore, the explained and elaborate phases have been shown to deepen reasoning skills and broaden students' capacity to apply concepts across varied contexts, resulting in consistent gains in learning outcomes.

Moreover, the stability of scores observed in the posttest phase also indicates that the 5E model not only enhances learning outcomes but also strengthens the consistency of students' conceptual understanding. This finding aligns with the results reported by Wulandari et al. (2023), who emphasize that the iterative structure of the 5E learning cycle provides repeated opportunities for conceptual reinforcement, thereby reducing score variability at the final stage of learning. Thus, the effectiveness of instruction is reflected not only in the increase in mean scores but also in the more even distribution of students' understanding.

Furthermore, the improvement in students' abilities in this study supports the findings of Sari et al. (2023), which suggest that the 5E model directly facilitates the development of fundamental scientific skills such as observing, interpreting information, and

drawing logical conclusions. This pattern was evident in the present study, where participants demonstrated more consistent accuracy in their responses and an improved ability to connect concepts during the posttest.

Overall, the findings of this research confirm that the implementation of the 5E Learning Cycle model has a positive and significant impact on enhancing learning outcomes. The intervention characterized by hands-on exploration, guided discussion, and systematic conceptual reinforcement proved effective in improving cognitive performance while cultivating scientific ways of thinking. Therefore, the model is recommended as an effective instructional strategy for strengthening conceptual understanding as well as scientific process skills across diverse learning contexts.

## Conclusion

This study concludes that the STEM-based 5E Learning Cycle model effectively enhances students' scientific literacy and learning outcomes by engaging them in structured, inquiry-based, and STEM-oriented learning experiences. In accordance with the research objectives and abstract summary, the integration of exploration, elaboration, and contextual problem-solving activities supports students in developing stronger conceptual understanding, scientific reasoning, and the ability to apply science concepts meaningfully. These findings suggest that the STEM-based 5E Learning Cycle can be generalized as an effective instructional approach for science learning, particularly in teacher education and similar educational contexts. From a practical perspective, this model provides educators with a feasible framework for designing active and student-centered science instruction using simple learning media and real-world contexts to promote scientific literacy and improve learning outcomes.

## Acknowledgments

The authors would like to express their sincere gratitude to Universitas Negeri Yogyakarta, Dr. Fery Muhamad Firdaus, S.Pd., M.Pd., and Prof. Yoppy Wahyu Purnomo, S.Pd., M.Pd., for their unwavering support, constructive guidance, and meaningful contributions throughout the development of this article.

## Author Contributions

Conceptualization, FMF, OMS, and PH.; methodology, FMF.; validation, OMS and PH.; formal analysis, FMF.; investigation, FMF.; resources, OMS and PH.; data curation, FMF.; writing - original draft preparation, FMF.; writing - review and editing, OMS and PH. All authors have read and agreed to the published version of the manuscript.

## Funding

The researchers financed this study independently without external funding support.

## Conflicts of Interest

No conflicts of interest were reported by the authors.

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