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The Effectiveness of the Phet-Assisted Learning Cycle 5E Model to Improve Students' Critical Thinking Skills and Science Literacy on the Topic of Sound Waves

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Abstract: This study aims to evaluate the effectiveness of the Learning Cycle 5E model assisted by PhET simulations in improving students' critical thinking skills and science literacy on the topic of sound waves. A quasi-experimental design was used with three classes: an experimental class (Learning Cycle 5E + PhET), control class 1 (Learning Cycle 5E only), and control class 2 (direct instruction). Classes were randomly selected from grade XI students at SMA Negeri 1 Piyungan. Instruments consisted of a critical thinking essay test and a science literacy multiple-choice test, each covering four indicators and validated using Quest. PhET simulations ("Sound" and "Wave on a String") were integrated from the exploration to evaluation phases. The Kruskal-Wallis test showed significant differences between groups ($p = 0.001$). The experimental class achieved the highest posttest scores: 90.68 (SD = ±4.8) in critical thinking and 68.92 (SD = ±6.2) in science literacy. The most significant improvements occurred in evaluating arguments and understanding science concepts. These results suggest that integrating PhET simulations into the Learning Cycle 5E model effectively enhances students' conceptual understanding, critical thinking, and science literacy. This approach can be recommended as an alternative learning strategy in physics education, particularly for abstract and complex topics.

Keywords: Critical thinking; Learning cycle 5E; PhET simulation; Science literacy

Introduction

The rapid development of science and technology demands that education adapt to 21st-century needs, where students are expected to possess strong critical thinking skills and scientific literacy. The Merdeka Curriculum in Indonesia emphasizes these competencies to better prepare students for global challenges. However, students' skills in both areas remain relatively low, particularly in physics (Ridho et al., 2020). Research indicates that critical thinking skills are still in the low category (Affandy et al., 2019; Wayudi et al., 2020), and science literacy is similarly lacking, partly due to the limited use of innovative learning strategies (Sutrisna, 2021). This highlights the need for learning models that not only support conceptual understanding but also foster cognitive skills and scientific literacy holistically.

Physics presents a unique challenge due to the abstract nature of its content. One particularly difficult topic is sound waves, as the phenomena cannot be directly perceived by the senses. This makes it hard for students to relate theoretical concepts to real-world phenomena such as resonance, the Doppler effect, and sound propagation (Cahyanto et al., 2022). To address this, learning approaches that concretely represent abstract ideas are essential.

The Learning Cycle 5E model—comprising Engage, Explore, Explain, Elaborate, and Evaluate—encourages students to construct knowledge through exploration and reflection, making it ideal for developing critical thinking and scientific literacy. Studies have shown that

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this model significantly enhances students' critical thinking compared to conventional methods (Amaliyah et al., 2023) and is also effective in improving science literacy (Wiguna et al., 2017).

To enrich the learning experience, the 5E model can be integrated with PhET simulations—interactive, technology-based tools that allow students to visualize abstract physics concepts like sound waves through realistic, manipulable animations. These simulations help bridge the gap between theory and practice by prompting observation, prediction, and conclusion-drawing—key components of scientific thinking and literacy. In learning about sound waves, students can explore how sound propagates, how frequency influences pitch, and how resonance occurs in different tube configurations. Research by Purfiyansyah et al. (2023) confirms that combining the 5E model with PhET simulations significantly improves students' critical thinking and learning outcomes in physics.

While many strategies have been explored to enhance 21st-century skills, studies focusing specifically on the use of the Learning Cycle 5E model supported by PhET simulations in sound wave instruction are still limited. Therefore, this study aims to evaluate the effectiveness of this integrated approach in enhancing students' critical thinking and science literacy, particularly on the topic of sound waves.

Method

This study employs an experimental design using a pretest-posttest control group design. This research approach was chosen to assess the effectiveness of the Learning Cycle 5E model assisted by PhET simulations in enhancing students' critical thinking skills and science literacy. Experimental research aims to establish causal relationships by comparing the effects of different treatments (Sundari et al., 2024). In this study, three groups were used: an experimental group, contrast group 1, and contrast group 2. The effectiveness of the applied treatment was evaluated by comparing the outcomes among these groups, as outlined in Table 1.

Table 1. Research design

Class	Pretest	Treatment	Posttest
Experiment	X1	Y1	X2
Contrast 1	X1	Y2	X2
Contrast 2	X1	Y3	X2

Information:
X1 : The level of initial knowledge of students
X2 : The level of final knowledge of the learner
Y1 : Cycle 5E Learning Model + PhET Simulation
Y2 : Cycle 5E Learning Model
Y3 : Direct Interaction Learning Model

The population in this study were all grade XI students of SMA Negeri 1 Piyungan in the 2024/2025 school year. The sample consisted of three classes randomly selected using an online random picker tool. Before the treatment was given, an initial homogeneity test was conducted based on pretest scores to ensure that the initial abilities of the three classes were equal.

This study involved three classes with different learning treatments, namely experimental class with Learning Cycle 5E model assisted by PhET simulation, control class 1 with Learning Cycle 5E model without PhET, and control class 2 with Direct Instruction learning model. The treatment was carried out in four meetings during one week of learning on sound waves material.

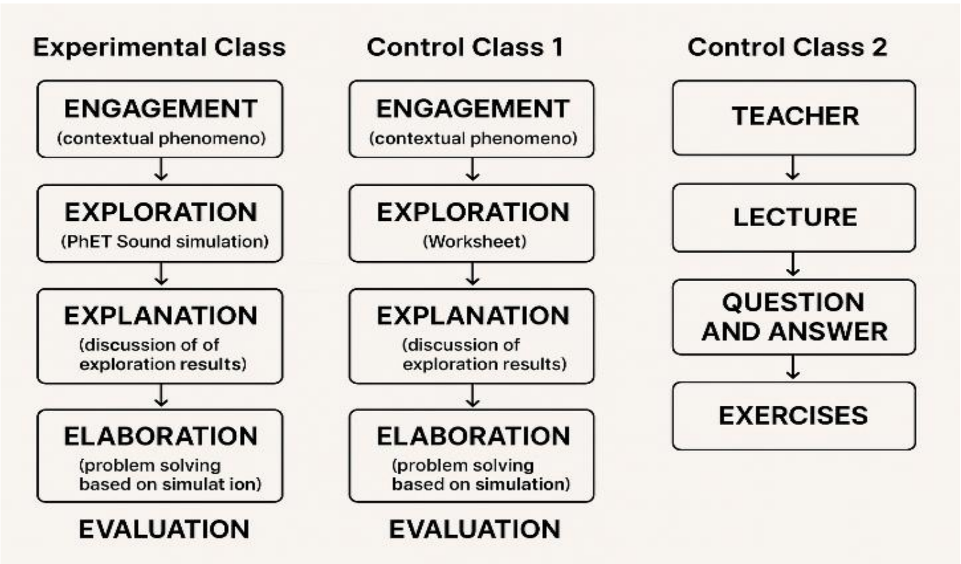

Figure 1. Cart

The collected data will be analyzed through several stages, including empirical validity and reliability tests, as described below.

Empirical Validity

Empirical validity is carried out after content validity is carried out to determine the validity of pretest-posttest items. Empirical validity was assessed using the Quest program based on the Rasch model. Instrument test data from 60 XII grade students were entered into the Quest program in .txt format, with answers coded according to the system format. The program generates INFIT Mean Square (INFIT MNSQ) parameters that indicate the fit between the empirical data and the theoretical model. Question items are declared empirically valid if the INFIT MNSQ value is in the range of 0.77 to 1.30. Question items with values outside this range are considered for revision or elimination.

Empirical Reliability

Empirical reliability was tested using the Quest program based on the results of a limited trial on 60 XII grade students. Student answer data was entered into the Quest program and analyzed using the Rasch Model approach. The reliability value is obtained from the Summary of Estimation Case output. The results obtained are classified according to Sugiyono (2017) as follows (Table 2).

Table 2. Reliability value categories

Validity Coefficient	Validity Category
$0.80 \leq R \leq 1.00$	Very high
$0.60 \leq R < 0.79$	High
$0.40 \leq R < 0.59$	Keep
$0.20 \leq R < 0.39$	Low
$0.00 \leq R < 0.19$	Very low

After the reliability test, inferential data analysis was conducted using prerequisite tests to determine the appropriate method for testing the research hypothesis. The prerequisite tests used in this study included normality and homogeneity tests.

Normality Test

The normality test aims to determine whether the distribution of the data being analyzed is normally distributed or not. The data used for this analysis is in the form of posttest results of critical thinking skills and science literacy. Normality test analysis was conducted using the Shapiro-silk test. The analysis was conducted using the SPSS program. Normality data can be seen based on the provisions of the significant level (Asymp. Sig). If the significant level (Sig.) > 0.05 then the data is normally distributed.

Homogeneity Test

Homogeneity test was conducted on critical thinking ability and science literacy data. The statistical analysis used is the levene test with the SPSS program. Homogeneity of data can be seen based on the provisions of the significant level (Asymp. Sig). If the significant level (Sig.) & gt; 0.05 then the data is normally distributed. If the prerequisite tests are not met, a non-parametric analysis will be performed using the Kruskal-Wallis test for hypothesis testing. The decision criteria for the Kruskal-Wallis test are as follows, H_0 is rejected if Sig. < 0.05; H_0 is accepted if Sig. > 0.05.

Hypothesis testing is done through the SPSS program with the initial stage of normality test using Shapiro-Wilk and homogeneity test using Levene. Data is declared normal and homogeneous if the significance value & gt; 0.05. Because most of the data did not meet these assumptions, the Kruskal-Wallis test was used as a non-parametric analysis to test differences between groups. Critical thinking ability was measured using eight description questions based on Ennis (1985) indicators, with 0-4 scoring, while science literacy was measured using twelve multiple-choice questions based on indicators from OECD (2016).

Critical thinking is the ability to actively and continuously analyze, present, evaluate, and conclude information with the aim of obtaining accurate and accountable understanding. Meanwhile, science literacy is a skill to analyze problems, understand scientific phenomena, obtain facts through experiments, and apply both in the context of everyday life and science issues.

Result and Discussion

This study investigates the effectiveness of the Learning Cycle 5E model assisted by PhET simulations in enhancing students' critical thinking and science literacy on the topic of sound waves. Data were collected through pretests and posttests, using essay questions to assess critical thinking and multiple-choice questions for science literacy. The results were analyzed descriptively and inferentially across three groups: the experimental class (Learning Cycle 5E + PhET), contrast class 1 (Learning Cycle 5E), and contrast class 2 (direct instruction).

This study employs an experimental research design to assess the effectiveness of the Learning Cycle 5E model assisted by PhET simulations in teaching sound waves. The goal is to enhance students' critical thinking skills and science literacy. The research will be conducted in February 2025 at SMA Negeri 1 Piyungan, involving students from classes XI F1, XI F2, and XI F3.

To evaluate the effectiveness of the Learning Cycle 5E model, supporting materials such as teaching modules, student worksheets (LKPD), and assessment instruments are required to measure improvements in students' critical thinking skills and science literacy. The assessment instruments will be tested on 60 grade XII students at SMA Negeri 1 Piyungan, as they have already studied sound wave material. The critical thinking skills test consists of eight essay questions, while the science literacy test includes twelve multiple-choice questions. The collected data will be analyzed using the Quest program, and the results of the validity test for critical thinking skills and science literacy will be presented in Table 3.

Table 3. Results of validation and reliability of critical thinking instruments

Question Number	INFIT MNSQ	Category
1	0.84	Valid
2	0.75	Invalid
3	0.75	Invalid
4	1.41	Invalid
5	1.34	Invalid
6	0.95	Valid
7	0.79	Valid
8	1.02	Valid

Based on the table, four questions (items 2, 3, 4, and 5) were found to be invalid, as their INFIT Mean of Square (INFIT MNSQ) values fall outside the acceptable range of 0.77 to 1.30. Meanwhile, the validity results for the science literacy assessment are as follows (Table 4).

Table 4. Results of validation and reliability of science literacy instruments

Question Number	INFIT MNSQ	Category
1	1.01	Valid
2	1.04	Valid
3	0.93	Valid
4	0.49	Invalid
5	1.21	Valid
6	0.94	Valid
7	1.16	Valid
8	1.39	Invalid
9	0.90	Valid
10	0.75	Invalid
11	0.81	Valid
12	1.17	Valid

Table 4 indicates that three questions (items 4, 8, and 10) are invalid, as their INFIT Mean of Square (INFIT MNSQ) values fall outside the acceptable range of 0.77 to 1.30. The reliability test results for the critical thinking skills and science literacy instruments are presented in Table 5.

Table 5 presents the reliability results, showing a reliability score of 0.49 for critical thinking skills and 0.62 for science literacy. These scores fall into the Medium and High categories, respectively. Therefore, the critical thinking skills instrument is considered reliable and suitable for use in field tests.

Table 5. Results of reliability of critical thinking instruments and science literacy

Variable	Reliability of estimate	Category
Critical Thinking	0.49	Keep
Science Literacy	0.62	Tall

A descriptive analysis was conducted to assess students' initial understanding before and after the treatment. This analysis involved pre-test and post-test data on critical thinking skills and science literacy. The experimental class received instruction using the Learning Cycle 5E model assisted by PhET simulations.

In the experimental class, learning was conducted using the Learning Cycle 5E model integrated with PhET simulations. The simulations were embedded throughout each stage of the 5E model to reinforce discovery-based learning and enhance conceptual understanding. The integration of PhET at each stage is described as follows (Table 6).

Table 6. Learning stages

Level	Post-test Frequency	Post-test Percentage
Engagement	Students watch a video or are given triggering questions about sound waves.	The teacher shows a snapshot of the “Sound” simulation from PhET to spark curiosity.
Exploration	Students make independent observations of sound waves.	Students use the PhET simulations “Sound” and “Wave on a String” to try different scenarios.
Explanation	Students discuss their observations and explain the concept of sound.	Students compare graphs and animations in the simulations to explain relationships between variables.
Elaboration	Students complete real-life context-based problems or tasks.	Students simulate real events and explain scientific phenomena.
Evaluation	Students complete formative tests and reflection.	Students use the simulation integrated worksheet for evaluation.

The use of PhET has been shown to increase student engagement and understanding of abstract concepts (Adams et al., 2008; Wieman & Perkins, 2006).

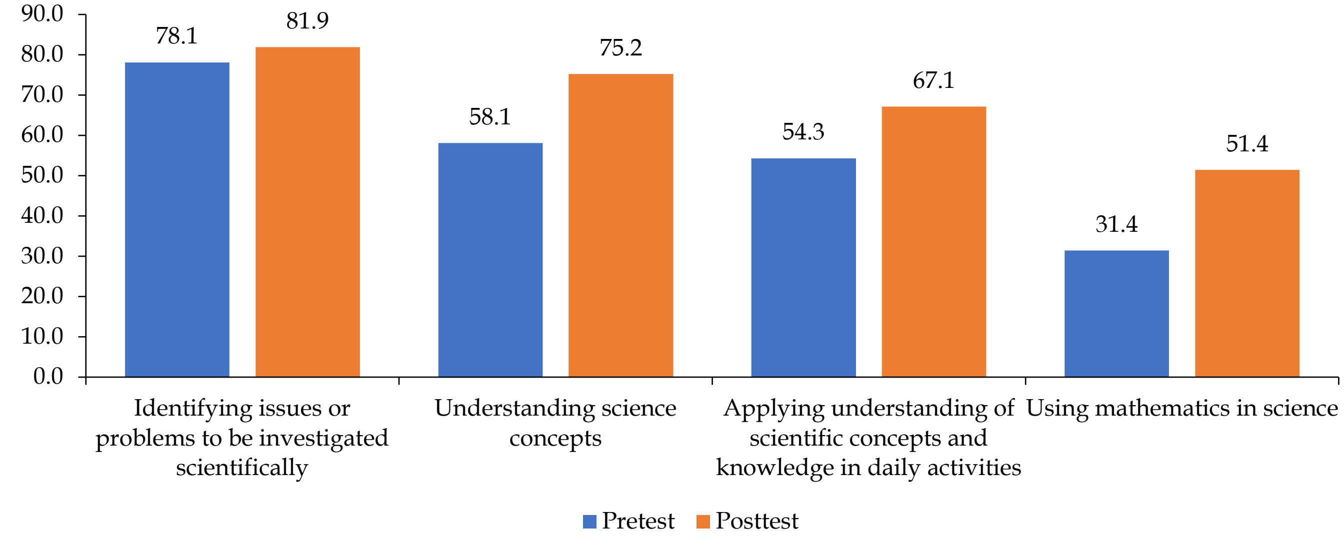

Figure 2. Level of critical thinking ability of experimental class

Table 7. Percentage of critical thinking ability

Level	Pre-test Frequency	Pre-test Percentage (%)	Post-test Frequency	Post-test Percentage (%)
Excellent	0	0	29	82.9
Good	0	0	1	2.8
Enough	6	17.2	2	5.7
Less	29	82.8	3	8.6

The data above shows an increase in the profile of students' critical thinking skills in the experimental class. Before the treatment, the average critical thinking score was 39.57, with 82.8% of students categorized as needing guidance. After learning with the Learning Cycle 5E model-based teaching module assisted by PhET simulations, students' critical thinking skills showed significant improvement. This is reflected in the post-test results, where the average score increased to 90.68, with only 8.6% of students still requiring guidance.

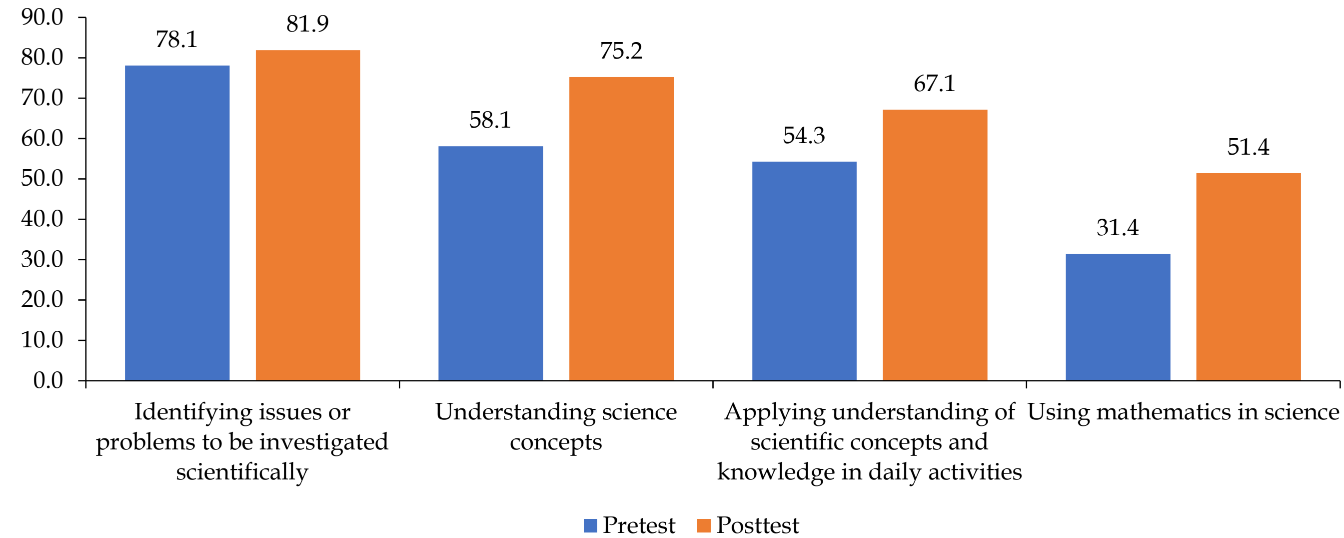

Figure 3. Experimental class science literacy ability level

The data in Figure 3 and Table 8 shows an increase in the profile of science literacy skills in students in the experimental class. Before the treatment, the average science literacy score was 55.57, with 60% of students categorized as needing guidance. After learning with the Learning Cycle 5E model-based teaching module assisted by PhET simulations, students' science literacy skills improved. This is evident from the post-test results, where the average score increased to 68.92, with only 25.7% of students still requiring additional guidance.

In contrast class 1, learning was conducted using the Learning Cycle 5E model. The following are the results obtained for critical thinking skills and their corresponding percentages in contrast class 1.

Table 8. Percentage of science literacy ability

Level	Pre-test Frequency	Pre-test Percentage (%)	Post-test Frequency	Post-test Percentage (%)
Excellent	3	8.6	12	34.3
Good	3	8.6	10	28.6
Enough	8	22.9	4	11.4
Less	21	60	9	25.7

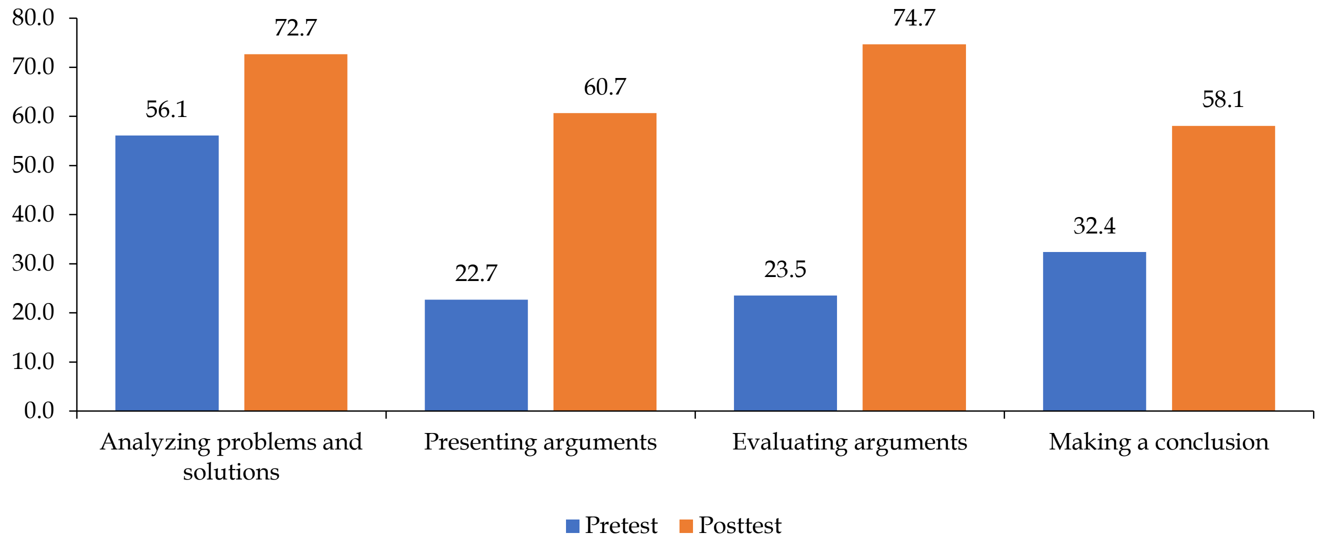

Figure 4. Critical thinking ability levels of contrast class 1

Table 9. Percentage of critical thinking skills

Level	Pre-test Frequency	Pre-test Percentage (%)	Post-test Frequency	Post-test Percentage (%)
Excellent	0	0	2	5.6
Good	1	2.8	7	19.4
Enough	2	5.6	9	25
Less	33	91.7	18	50

Based on the data above, it is known that the contrast class 1 showed progress in critical thinking skills after learning using the Learning Cycle 5E module. The average critical thinking score increased from 32.4 to 66.66, while the percentage of students needing guidance decreased from 91.7 to 50%.

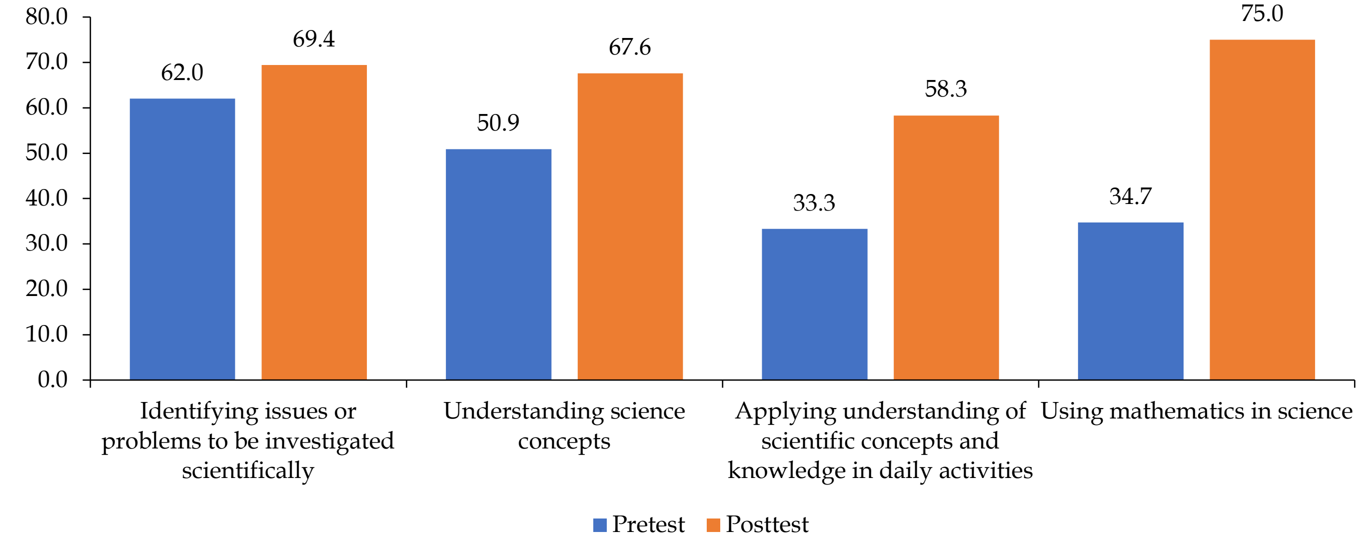

Figure 5. Contrast class 1 science literacy level

Table 10. Percentage of science literacy ability

Level	Pre-test Frequency	Pre-test Percentage (%)	Post-test Frequency	Post-test Percentage (%)
Excellent	0	0	7	29.4
Good	3	8.3	6	16.7
Enough	4	11.1	11	30.6
Less	29	80.6	12	33.3

The data above shows an increase in the science literacy skills of students in the contrast class 1. Before learning, the average science literacy score was 45.24, with 80.6% of students categorized as needing guidance. After using the Learning Cycle 5E model-based teaching module, the average post-test score increased to 67.59, with only 33.3% of students still requiring additional guidance.

In contrast class 2, learning was conducted using the Direct Instruction model. The following are the results for science literacy skills and their corresponding percentages in contrast class 2.

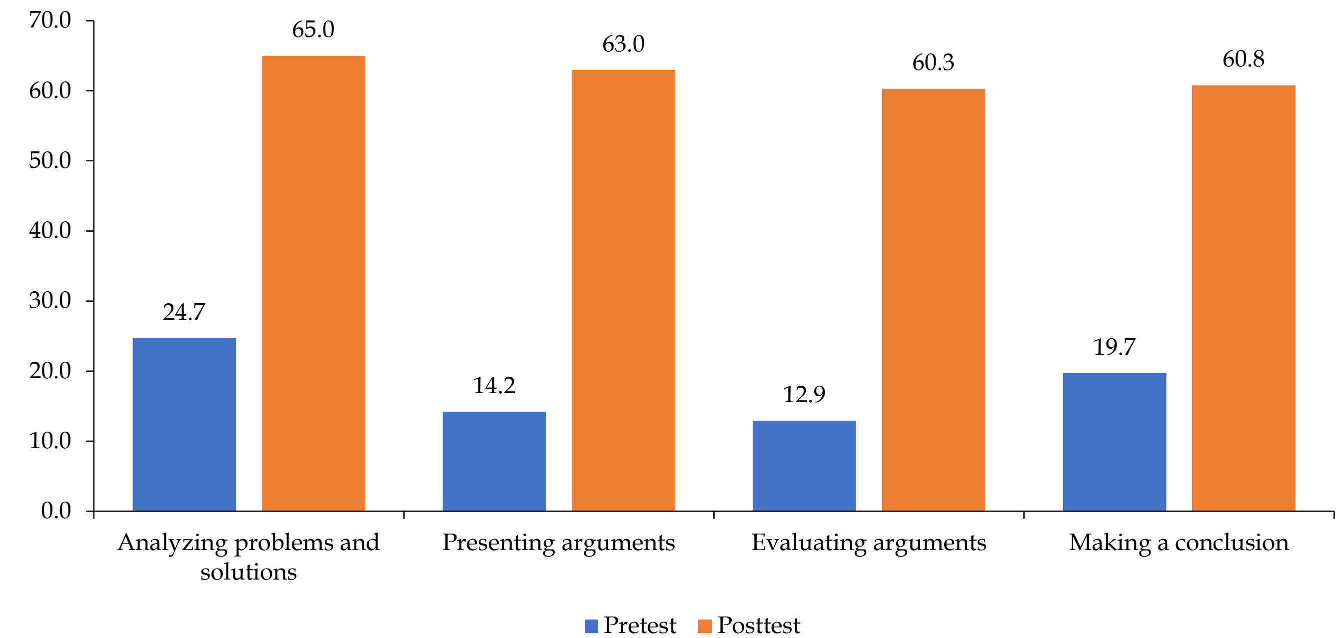

Figure 6. Critical thinking ability level of contrast class 2

Table 11. Percentage of critical thinking skills

Level	Pre-test Frequency	Pre-test Percentage (%)	Post-test Frequency	Post-test Percentage (%)
Excellent	0	0	9	25
Good	1	2.8	6	16.7
Enough	0	0	6	16.7
Less	35	97.2	15	41.7

The data above shows an increase in the profile of students' critical thinking skills in contrast class 2. Before the intervention, the average critical thinking score was 17.9, with 97.2% of students categorized as needing guidance. After learning with the Direct Instruction model-based teaching module, students' critical thinking skills improved, as reflected in the post-test average score of 62.27, with only 41.7% of students still requiring guidance.

Table 12. Percentage of science literacy ability

Level	Pre-test Frequency	Pre-test Percentage (%)	Post-test Frequency	Post-test Percentage (%)
Excellent	0	0	7	19.4
Good	2	5.6	6	16.7
Enough	3	8.3	3	8.3
Less	31	86.1	20	55.6

The data in Figure 7 and Table 12 shows that there is an increase in the profile of science literacy skills of students in contrast class 2. Before the intervention, the average science literacy score was 43.98, with 86.1% of students classified as needing guidance. After learning with teaching modules using the Direct Instruction model, students' science literacy skills improved, as reflected in the post-test average score of 60.88, although 55.6% of students still required further guidance.

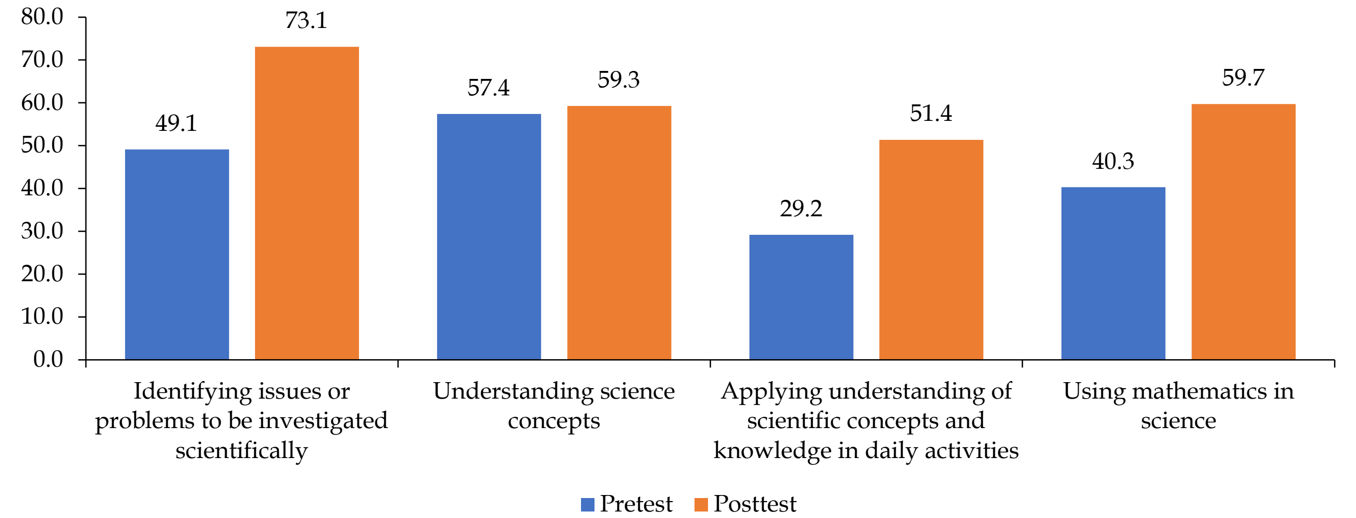

Figure 7. Contrast class 2 science literacy level

The comparison of critical thinking skills was analyzed based on the average pretest and posttest scores across classes that received different treatments. The results are presented in the following figure.

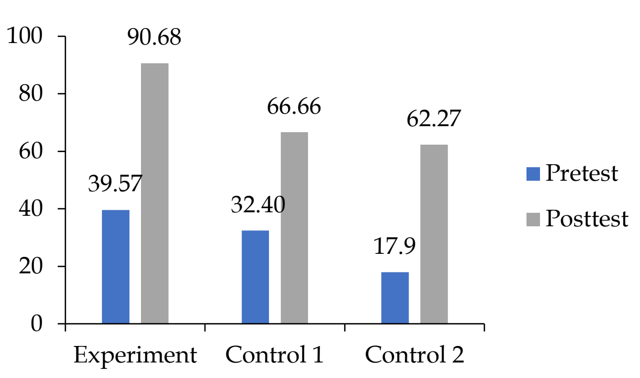

Figure 8. Comparison of critical thinking skills

The figure above illustrates that the critical thinking ability scores in the experimental class showed the most significant improvement across all indicators. The average critical thinking score increased from 39.57 (Poor) to 90.68 (Excellent), highlighting the effectiveness of the investigative approach in the Learning Cycle 5E model, enhanced by concept visualization through PhET simulations.

Contrast group 1, which implemented the Learning Cycle 5E model without simulations, also showed improvement, though less than the experimental group. This suggests that while the 5E model supports higher-order thinking, it is less effective in visualizing abstract concepts such as sound waves.

Contrast group 2, which followed a direct instruction approach, demonstrated the lowest gain. This may be attributed to the teacher-centered method, which limits students' active engagement in scientific exploration and reasoning.

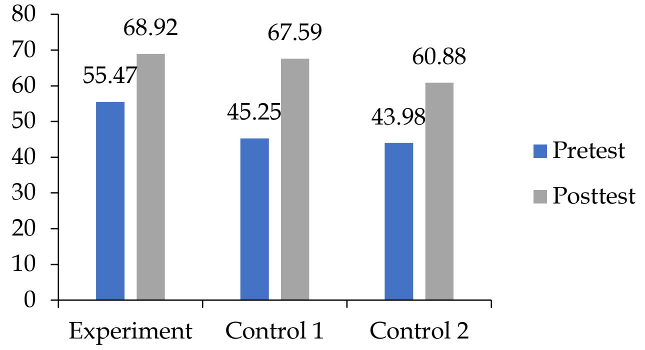

Figure 9. Comparison of science literacy abilities

Based on the figure above, there are noticeable differences in science literacy skills among the experimental class, contrast class 1, and contrast class 2. The posttest scores show that the experimental class experienced a greater increase compared to the other classes.

The key factor distinguishing the experimental group from the other two groups was the active engagement of students in visual and simulative exploration. PhET simulations enabled students to observe cause-and-effect relationships, conduct virtual experiments, and independently evaluate the results. This process not only enhanced conceptual understanding but also fostered critical reasoning and scientific reflection.

To determine whether the collected data follows a normal distribution, a normality test was conducted using the Shapiro-Wilk test in the SPSS program. The results of this test serve as the basis for selecting the appropriate statistical analysis techniques for further data processing. The normality test results are presented in Table 13.

Table 13. Results of the normality test

Variable	Class	Shapiro-Wilk Statistic	Df	Mr.
Critical Thinking Skills	Experiment	0.876	35	0.001
	Control 1	0.965	36	0.313
	Control 2	0.913	36	0.008
Science Literacy Ability	Experiment	0.897	35	0.009
	Control 1	0.913	36	0.006
	Control 2	0.908	36	0.003

Based on the table above, the significance (Sig.) value for each variable is less than 0.05, indicating that the data for each variable is not normally distributed. To further analyze the data distribution, a homogeneity test for critical thinking skills and science literacy was conducted using the SPSS program with Levene's Test. The results of this test are presented in Table 14.

Table 14. Homogeneous test results

Variable	Levene Statistic	df1	df2	Mr.
Critical Thinking	20.676	2	104	0.001
Science Literacy	0.345	2	104	0.709

Based on the table above, the data distribution for students' science literacy improvement is homogeneous, as indicated by a significance value greater than 0.05. However, students' critical thinking skills data are not homogeneous, as the significance value is below 0.05.

The prerequisite test results show that the data are not normally distributed, with only one dataset having homogeneous variance. As a result, the data on critical thinking skills and science literacy do not meet the requirements for parametric statistical analysis. Therefore, hypothesis testing was conducted using a non-parametric method, specifically the Kruskal-Wallis test. The results of this test are presented in Table 15.

Table 15. Results of the Kruskal Wallis test

Variable	Kruskal-Wallis H	df	Asymp. Sig.
Critical Thinking	36.551	2	0.001
Science Literacy	19.030	2	0.001

Based on the table above, the Asymp. Sig. value for both science literacy and critical thinking skills is 0.001, indicating that the null hypothesis (H_0) is rejected. This suggests a significant difference among the research classes, demonstrating that the applied treatments in each class influenced students' science literacy and critical thinking skills.

To further assess the impact of the Learning Cycle 5E model with PhET simulations, an effect size analysis was conducted. This analysis, performed using the epsilon squared test, measures the extent of the teaching module's influence on improving students' science literacy and critical thinking skills. The results of the effect size analysis are presented in Table 16.

Table 16. Results of effect size analysis

Variable	Epsilon Grades	Category
Critical Thinking	1.027	Very powerful
Science Literacy	0.741	Strong

Referring to the table above, the effect size analysis indicates that science literacy skills fall into the strong category, while critical thinking skills are categorized as very strong. The epsilon score for science literacy was 0.741, whereas critical thinking skills achieved a score of 1.027.

Discussion

Physics learning tools are developed to support effective learning activities, following the guidelines of the Independent Curriculum. These tools are designed to align with the Learning Cycle 5E model for sound wave material, incorporating PhET simulations to enhance students' critical thinking skills and science literacy. By adopting an active and exploratory approach, this model enables students to construct their own understanding through five stages: Engagement, Exploration, Explanation, Elaboration, and Evaluation.

In the Engagement stage, students encounter contextual problems that spark curiosity and activate prior knowledge. The Exploration stage allows them to interact with PhET simulations, conduct investigations, and identify physics principles firsthand. During Explanation, students connect their findings to scientific concepts through discussion and reflection. The Elaboration phase encourages them to apply their understanding in new and more complex problem-solving scenarios. Finally, the Evaluatio stage assesses their comprehension and critical thinking through formative and summative evaluations. The integration of PhET simulations provides an interactive learning environment, visualizes abstract concepts, and facilitates virtual experimentation, ultimately enhancing students' critical thinking and science literacy.

This study examines the development of students' critical thinking and science literacy before and after applying the Learning Cycle 5E model assisted by PhET simulations. The research was conducted in three different classes with distinct instructional methods: Class XI F3 (experimental class) implemented the Learning Cycle 5E model with PhET simulations, Class XI F1 (contrast class 1) applied the Learning Cycle 5E model without PhET simulations, and Class XI F2 (contrast class 2) followed the Direct Instruction model. The learning process spanned four sessions, with the final session dedicated to a posttest on sound wave material. The effectiveness of this study was measured by evaluating the improvement in students' critical thinking and science literacy skills.

Assessment was based on the increase in pretest and posttest scores across all classes. Before the intervention, the experimental class had an average critical thinking score of 39.57, categorized as poor. However, after applying the Learning Cycle 5E model with PhET simulations, students demonstrated significant improvement, achieving an average score of 90.68. The experimental class outperformed the other groups in all critical thinking indicators. Constructivist learning model involving simulation is proven to significantly improve students' critical thinking skills (Nafisah & Fatmawati, 2024). In other words, the Learning Cycle 5E model effectively engages students in critical thinking, allowing them to relate physics concepts to real-world applications and develop a deeper understanding of the material.

In contrast class 1, which applied the Learning Cycle 5E model, students' critical thinking ability improved from the poor category to the fair category, with an average posttest score of 66.66. Among the assessed indicators, evaluating arguments showed the highest achievement in this class. Meanwhile, in contrast class 2, which used the Direct Instruction model, critical thinking skills improved from the less to the fair category, with an average score of 62.27, the lowest among the three classes. This indicates that contrast class 2 (F2) demonstrated lower critical thinking skills compared to the other groups.

At the beginning of the learning process, students in all classes exhibited low science literacy skills, requiring guidance. The experimental class, which received the Learning Cycle 5E model with PhET simulation, showed a significant improvement, reaching the sufficient category with an average posttest score of 68.92. Three indicators outperformed those in other classes: identifying scientific issues, understanding scientific concepts, and applying scientific knowledge in daily life. The Learning Cycle 5E model improves science literacy through an exploratory stage that emphasizes connections between theory and practice (Widana & Widyastiti, 2023). Therefore, the implementation of the Learning Cycle 5E model assisted by PhET simulation has been proven effective in enhancing science literacy, an essential skill in today's information-driven era.

In contrast class 1, which also applied the Learning Cycle 5E model (but without PhET simulation), science literacy skills improved from the less to the sufficient category, with an average posttest score of 67.59. The highest-achieved indicator in this class was using mathematics in science. Meanwhile, contrast class 2 experienced a similar improvement but recorded the lowest posttest score of 60.88, indicating that students in F2 (contrast class 2) had the weakest science literacy skills among the three groups.

The effectiveness of the Learning Cycle 5E model with PhET simulation can be evaluated based on the differences in learning outcomes across the three classes. In terms of critical thinking ability, the experimental class achieved the highest posttest score (90.68), followed by contrast class 1 (66.66) and contrast class 2 (62.27). Similarly, for science literacy skills, the posttest scores were 68.92 in the experimental class, 67.59 in contrast class 1, and 60.88 in contrast class 2. These results confirm that the Learning Cycle 5E model assisted by PhET simulation is the most effective approach in enhancing both critical thinking and science literacy skills among students.

The Kruskal-Wallis test analysis further confirms the effectiveness of the developed teaching module. The significance level of 0.001 for critical thinking skills and science literacy indicates a significant difference in learning outcomes across the classes with different treatments. This finding aligns with research by Widana & Widyastiti (2023), which highlights that the Learning

Cycle 5E model enhances students' conceptual understanding, critical thinking skills, and science literacy. The effectiveness of the Learning Cycle 5E model assisted by PhET simulation is also evident from the effect size analysis using epsilon squared. The results show an effect size of 1.027 (very strong category) for critical thinking skills and 0.741 (strong category) for science literacy skills. These findings confirm that the experimental class experienced greater improvement in critical thinking and science literacy compared to contrast class 1 and contrast class 2.

Conclusion

This study demonstrates that the Learning Cycle 5E model assisted by PhET simulations is effective in enhancing students' critical thinking skills and science literacy on the topic of sound waves. Significant gains were observed particularly in the indicators of evaluating arguments and drawing conclusions for critical thinking, as well as identifying scientific issues and understanding science concepts for science literacy. The experimental group achieved an average posttest score of 90.68 (SD = ±4.8) for critical thinking and 68.92 (SD = ±6.2) for science literacy. PhET simulations were integrated throughout all stages of the 5E model—serving as a stimulus during Engagement, a tool for visual exploration during Exploration, and a means to deepen and apply concepts during Explanation and Elaboration. The LKPD included exploration- and reflection-based tasks, such as constructing arguments using simulation data and applying wave concepts to real-life contexts. These findings support the use of the Learning Cycle 5E model with PhET simulations as an interactive strategy to improve the quality of physics instruction, particularly for abstract topics. The teaching module is adaptable for other science topics and can be expanded to assess higher-order thinking skills in the context of science literacy.

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Author Contributions

S. and R.P.: Conceptualization, methodology, software, validation, formal analysis, investigation, writing—original draft preparation, writing—review and editing, visualization, supervision, project administration, funding acquisition. R.P., P.W.P., and J.: Data curation, investigation, writing—review and editing.

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Conflicts of Interest

The authors declare that there is no conflict of interest in the preparation of this article.

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