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The Effect of Problem Based Learning Assisted by Liveworksheet for Critical Thinking on Senior High School

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Abstract

This study aims to examine the effect of Problem Based Learning (PBL) assisted by Liveworksheet for critical thinking skills on senior high school. This study employed a quasi-experimental method with a pretest-posttest control group design. The research participants consisted of 36 students in the experimental class and 36 students in control class using purposive sampling technique. The research data were obtained through a critical thinking skills test and a student response questionnaire. The average pretest score of the experimental class was 43.61, which increased to 64.86 for posttest. Meanwhile, the average pretest score for control class was 42.36, which increased to 54.72 for posttest. The results showed a significant difference in critical thinking skills between the experimental class and control class, with a significance value of 0.001 (<0.05). Furthermore, the N-Gain value of 0.3655 fell into the medium category, while the effect size value of 0.83 was classified as high. Student responses to the learning process also showed positive results, with an average percentage of 85%. generally, students who participated in learning using PBL assisted by interactive e-worksheets based on Liveworksheet integrated with PhET simulations achieved higher posttest scores in critical thinking skills compared to students for control class.

Keywords: Critical Thinking Skills, Liveworksheet, Problem Based Learning, Waves

INTRODUCTION

21st century of education emphasizes is the importance of developing higher-order thinking skills to address the challenges posed by advances in technology and science (Basri et al., 2024). Among the various higher-order thinking skills, critical thinking is one of the most important abilities because it enables students to evaluate information systematically, analyze arguments, and draw rational conclusions based on valid evidence (Dewi et al., 2025). The importance of improving critical thinking skills is also demonstrated by the results of global assessments such as PISA, which show that the abilities of Indonesian students, particularly in science, remain relatively low (Cahyani et al., 2025; PISA, 2023). In physics learning, critical thinking skills are highly necessary, especially in the topic of waves, as students are required to analyze the relationships between frequency, wavelength, period, and wave propagation phenomena. The topic of waves is also abstract and often leads to misconceptions if students only focus on using formulas without deeply understanding the concepts (Haerunnisa et al., 2022). Consequently, students often experience difficulties in interpreting wave phenomena scientifically and in connecting theoretical concepts to real-life events. Specifically, wave material requires critical thinking because of counterintuitive concepts, non-linear relationships between quantities, abstract superposition principles, and mathematical applications that require analysis.

Students' difficulties in understanding the concept of waves indicate that critical thinking skills in physics learning still need to be improved (Yusmar & Fadilah, 2023). However, the physics learning methods applied in schools still tend to focus on delivering theoretical material and solving routine problems, thus providing few opportunities for students to explore concepts in depth (Sari et al., 2022). This condition causes students to be less actively engaged in the learning process and to experience difficulties in connecting theoretical concepts to their application in real life (Soeharto & Csapó, 2022). Therefore, a learning approach is needed that is able to shift teacher-centered learning to student-centered learning, emphasizing not only the final outcome but also the students' thinking process in understanding, analyzing, and solving scientific problems (Wijnia et al., 2024).

A beneficial educational method for enhancing students' ability to think critically is PBL. This approach employs real-world issues as an educational foundation, motivating students to seek solutions through questioning, discussions, and reflective practices (Mardhani et al., 2022). In the realm of physics education, this method is particularly pertinent as it helps students connect theoretical concepts with actual events (Anggraini et al., 2025). Implementing PBL encourages greater student engagement as they recognize and tackle problems, leading to a more significant and enjoyable educational experience (Alfares, 2021).

The successful implementation of PBL depends not only on the presentation of problems but also on the availability of teaching materials that can help students develop structured thinking patterns and critical thinking skills (Jumhur et al., 2024). One such teaching material is the e-worksheet, which serves as a guide for student learning activities during the problem-solving process. In this study, the e-worksheet was developed using the Liveworksheet platform, an interactive digital medium that allows students to complete worksheets online with more engaging and responsive features (Aulia et al., 2024). The use of Liveworksheet supports student engagement in the learning process through interactive activities such as answering questions, observing information, and discussing problem solutions (Shafnahriyah & Sukarmin, 2026). Meanwhile, PhET simulations are used to help students visualize abstract wave concepts through virtual experiments, enabling students to more easily understand the relationships among wave concepts. The integration of PBL, Liveworksheet-based e-worksheets, and PhET simulations provides students with opportunities to actively engage in investigation, analysis, and problem-solving processes oriented toward the development of critical thinking skills (Miranda et al., 2025). Research by (Wulandari et al., (2025) also shows that the use of interactive Liveworksheet-based e-worksheets in PBL learning can improve students' critical thinking skills.

Although previous research has shown that the implementation of PBL assisted by Liveworksheet can improve students' critical thinking skills, most of these studies have still focused on specific topics such as temperature and heat (S. Dewi & Nisa', 2025). Research on wave material has been conducted by Prihandono et al., (2023), but that study used a classroom action research approach that focused more on improving the learning process within a single class without a comparison group. As a result, the study has not been able to provide a strong comparative picture of the effect of using the learning model on students' critical thinking skills. Furthermore, the integration of PhET simulations into learning assisted by Liveworksheet-based e-worksheets on wave material is still rarely studied, even though virtual simulations can help students visualize abstract wave concepts through exploration and interactive experimentation activities. Therefore, this study employs a quasi-experimental design with an experimental class and a control class to provide a clearer picture of the effect of implementing the PBL assisted by Liveworksheet-based e-worksheets integrated with PhET simulations on students' critical thinking skills in wave material.

METHODS

This study employed a quantitative approach with a quasi-experimental design in the form of a pretest-posttest control group design. This design involved two groups, namely the experimental class and the control class, to compare students' critical thinking skills before and after the learning treatment was administered. The research was conducted in February 2026 at SMAN 3 Pamekasan with eleventh-grade students as the research subjects. The sampling technique used was purposive sampling. The selection of sample classes was based on several criteria, namely: (1) both classes were taught by the same physics teacher, (2) both classes had relatively equivalent academic abilities based on previous physics scores, and (3) both classes had relatively similar learning schedules and facilities. Based on these criteria, class XI A1 was designated as the experimental class and class XI A2 as the control class. The determination of the classes was carried out through consultation with the physics subject teacher to ensure that the research process could run smoothly.

Before the treatment was given, both groups were first given a pretest to identify students' initial critical thinking skills. The results of pretest were then used as a basis for analyzing the equivalence of initial abilities between the experimental class and control class before the implementation of the learning treatment. Information regarding the research sample and the implementation of the learning process is presented in Table 1.

Table 1. Research sample

Class	Treatment	Learning Implementation
XI A1 (Experiment)	Learning process using PBL assisted by the Liveworksheet application integrated with PhET simulations	The learning was conducted over three meetings, with each meeting lasting 90 minutes. The wave sub-materials taught included wave characteristics, wave equations, as well as transverse and longitudinal waves. Students worked in groups using interactive e-worksheets via Liveworksheet integrated with PhET simulations. Through these e-worksheets, students were guided to conduct investigations, analyze wave phenomena, answer analytical questions, and solve contextual problems in a structured manner according to the stages of the PBL.
XI A2 (Control)	Learning process using Discovery Learning without the assistance of learning media	The learning was conducted over three meetings, each lasting 90 minutes, with the same sub-materials as the experimental class. The learning process used the Discovery Learning assisted by PhET simulations, teacher explanations, and class discussions. However, the use of PhET simulations in the control class was not accompanied by interactive e-worksheets based on Liveworksheet that contained structured procedures and analytical questions, so that students' exploration and analysis activities were more limited.

The research instrument consisted of a critical thinking ability test and a student response questionnaire regarding the use of Liveworksheet on mechanical wave material. The critical thinking ability test was developed based on Ennis's five indicators, namely providing simple explanations, building basic skills, drawing conclusions, providing further explanations, and managing strategies and tactics. The instrument took the form of contextual essay questions related to the concepts of mechanical waves. As an example, for the indicator of providing simple explanations, students were asked to explain the formation of waves on a rope based on a given vibration event. For the indicator of drawing conclusions, students were asked to analyze the relationship between frequency, wavelength, and period based on the provided wave data or graph. The assessment of student answers used an analytic rubric with a scale of 1 to 4 for each Ennis indicator. A score of 4 was given when the answer was conceptually correct, the argumentation was relevant, and it demonstrated deep understanding. A score of 3 was given when the answer was correct but incomplete. A score of 2 was given when the answer was less accurate but still pointed toward the concept, while a score of 1 was given when the answer was inaccurate and inconsistent with the concept. The scoring rubric cited in Sundari & Sarkity (2021) article is presented in Table 2.

Table 2. Critical thinking skills scoring rubric

No	Category	Scoring Rubric
1	Provide a simple explanation	4. The answer to the question is accurate, provides the most appropriate argument, is directed toward the concept, demonstrates a deep understanding of the concept, and uses good and correct language. 3. The answer to the question is accurate, provides a relevant argument, is directed toward the concept, and uses good and correct language. 2. The answer to the question is less accurate, but the answer is directed toward the concept. 1. The answer to the question is inaccurate and the answer is not directed toward the concept.
2	Building basic skills	4. Identification of evidence and observation results is accurate, provides the most appropriate argument, the answer is directed toward the concept, demonstrates a deep understanding of the concept, and uses good and correct language. 3. Identification of evidence and observation results is accurate, provides a relevant argument, the answer is directed toward the concept, and uses good and correct language. 2. Identification of evidence and observation results is less accurate, but the answer is directed toward the concept. 1. Identification of evidence and observation results is inaccurate and the answer is not directed toward the concept.
3	Making conclusions	4. Deduces logically, provides the most appropriate argument, the answer is directed toward the concept, demonstrates a deep understanding of the concept, and uses good and correct language. 3. Deduces logically, provides a relevant argument, the answer is directed toward the concept, and uses good and correct language. 2. Deduces logically but the answer is not directed toward the concept. 1. Deduces illogically and the answer is not directed toward the concept.
4	Make further explanation	4. Defines the content accurately, provides the most appropriate argument, the answer is directed toward the concept, demonstrates a deep understanding of the concept, and uses good and correct language. 3. Defines the content accurately, provides a relevant argument, the answer is directed toward the concept, and uses good and correct language. 2. Defines the content less accurately, but the answer is directed toward the concept. 1. Defines the content inaccurately and the answer is not directed toward the concept.
5	Setting strategy and tactics	4. Determines the appropriate solution, provides the most appropriate argument, the answer is directed toward the concept, demonstrates a deep understanding of the concept, and uses good and correct language. 3. Determines the appropriate solution, provides a relevant argument, the answer is directed toward the concept, and uses good and correct language. 2. Determines a less appropriate solution, but the answer is directed toward the concept. 1. Determines an inappropriate solution and the answer is not directed toward the concept.

The content validity of the instrument was carried out through expert judgment by two physics expert lecturers to ensure the alignment of indicators, mechanical wave material, and question construction. The scoring of student answers was conducted by the researcher based on a rubric that had been developed to maintain consistency in assessment. The criteria for instrument validity were determined by comparing the calculated r value with the r table value of 0.355. An instrument was declared valid if the calculated r value > r table value. The criteria for instrument validity according to Rachmawati & Pradana (2025) are presented in Table 3.

Table 3. Validity test classification

Test Value	Description
r calculated < r table	Invalid
r calculated > r table	Valid
df = (n-2)	r table value

The results of instrument validity test

using Product Moment correlation are presented in Table 4.

Table 4. Instrument Validity Test Results

No Question	r table	r calculated	information
1	0.355	0.343	Invalid
2	0.355	0.365	Valid
3	0.355	0.646	Valid
4	0.355	0.667	Valid
5	0.355	0.729	Valid
6	0.355	0.478	Valid
7	0.355	0.772	Valid
8	0.355	0.724	Valid
9	0.355	0.617	Valid
10	0.355	0.736	Valid

Based on validity test results, 9 out of 10 question items were declared valid and 1 question item was declared invalid, so the instrument is suitable for use in the research.

The instrument reliability criteria refer to the Cronbach's Alpha value. The instrument reliability criteria according to Rachmawati & Pradana (2025) are presented in Table 5.

Table 5. Instrument reliability criteria

Alpha Range	Category
r < 0,20	Very low
0,20 < r < 0,40	Low
0,40 < r < 0,70	Moderate
0,70 < r < 0,90	High
0,90 < r < 1,00	Very High

The results of the instrument reliability test using Cronbach's Alpha are presented in Table 6.

Table 6. Instrument Reliability Test Results

Cronbach's Alpha	N of Item	information
0.809	10	High

The Cronbach's Alpha value of 0.809 indicates that the instrument has high reliability, so it is declared reliable and suitable for use in the research.

The research data were analyzed through several stages. The initial stage involved a descriptive analysis of the average pretest and posttest scores in the experimental class and the control class to determine the overview of students' initial abilities and final abilities after learning. Subsequently, prerequisite tests were conducted in the form of normality tests and homogeneity tests. The normality test was used to determine whether the data were normally distributed, while the homogeneity test was used to determine the equality of variances between the experimental class and the control class. The data were declared to meet parametric assumptions if the significance value was greater than 0.05. After the data met the prerequisite tests, an independent sample t-test was conducted to examine the differences in students' critical thinking skills between the experimental class and the control class. If the pretest scores between the two classes were relatively not far apart, the t-test was performed on the posttest scores of both classes to determine the differences in students' critical thinking skills after being given different learning treatments. The decision-making basis used a significance level of 0.05. If the significance value is less than 0.05, then there is a significant difference between the two classes, whereas if the significance value is greater than 0.05, then there is no significant difference. Furthermore, an effect size analysis was conducted to determine the magnitude of the effect of implementing the Problem Based Learning (PBL) assisted by Liveworksheet on students' critical thinking skills. The N-gain test was used to determine the improvement in students' critical thinking skills before and after learning in each class. Subsequently, a student response analysis was conducted to determine students' reactions to the use of Liveworksheet in the learning process in the experimental class. If the data did not meet the normality and homogeneity assumptions, a non-parametric test was used.

To evaluate the effect of the intervention on students' critical thinking skills, an effect size analysis was conducted using Cohen's d formula as referred to in Glass (Rikizaputra et al., 2021). In this study, the effect size was calculated based on the difference in mean posttest scores between the experimental class and the control class using the pooled standard deviation. The formula used is as follows:

$$ES = \frac{\widetilde{X}1 - \widetilde{X}2}{Sspooted} \times 100\% \quad (1)$$

Description:

ES = Effect size value

$\tilde{X}1$ =Mean of the experimental class

$\tilde{X}2$ = Mean of the control class

$S_{spooted}$ = Standard deviation of control class

To calculate Sspooted (Sgab) with the following formula:

$$Sspooted = \sqrt{\frac{(n_1 - 1)\, sd_1^2 + (n_2 - 1) sd_2^2}{n_1 + n_2}} \quad (2)$$

Description:
Sspooted = Combined standard deviation
n_1 = Number of students in the experimental class
n_2 = Number of students in the control class
Sd_1 = Standard deviation of the experimental class
Sd_2 = Standard deviation of control class.

Table 7. Criteria for effect size values

Range	Criteria
0,1 < ES < 0,5	Low
0,5 < ES < 0,8	Medium
0,8 < ES < 2,0	High

To determine the improvement in students' critical thinking skills before and after learning, an N-Gain analysis was conducted on the experimental class and the control class. This analysis was used to measure the effectiveness of the implementation of Problem Based Learning (PBL) assisted by Liveworksheet in improving learning outcomes based on students' pretest and posttest scores. The N-Gain value was calculated to determine the normalized improvement in students' critical thinking skills by comparing the difference between pretest and posttest scores to the ideal maximum score. The N-Gain formula is as follows (Rohayati et al., 2023):

$$\text{N - gain} = \frac{\text{posttest scores - pretest score}}{\text{maximum score - pretest score}} \quad (3)$$

The N-Gain analysis was used to compare the level of improvement between the experimental class and the control class in order to determine the effectiveness of the learning provided. The classification of N-Gain values refers to Hake (1998) as cited in Rohayati et al (2023), as presented in Table 8.

Table 8. N-Gain categories

N-Gain Value	Criteria
0,00 ≤ n ≤ 0,30	Low
0,30 ≤ n ≤ 0,70	Medium
0,70 ≤ n ≤ 1,00	High

Student response data were obtained through a questionnaire developed using a Likert scale with a score range of 1 to 5, consisting of positive and negative statements. The data obtained were then analyzed using quantitative descriptive analysis techniques to determine the level of student responses to the implementation of the Problem Based Learning (PBL) assisted by Liveworksheet e-worksheets.

The student response scores were then converted into percentages using the following formula:

$$p = \frac{\sum x}{\sum n} \times 100\% \quad (4)$$

Description:
p = Percentage score sought
$\sum x$ = Total average score obtained from respondents
$\sum n$ = Maximum total score

Furthermore, the percentage results were categorized based on the student response assessment criteria as referred to in Amalia et al. (2023), as presented in Table 9.

Table 9. Criteria for percentage of student response assessment

Percentage	Criteria
0% - 20%	Very Poor
21% - 40%	Poor
41% - 60%	Fairly Good
61% - 80%	Good
81% - 100%	Very Good

RESULTS AND DISCUSSION

RESULTS

The evaluation instrument used in this study consisted of five essay questions designed to measure students' critical thinking skills based on Ennis's indicators, namely focusing questions, analyzing arguments, performing clarification, making and evaluating observations, and drawing conclusions. Each essay question was developed to represent one critical thinking indicator so that all aspects of critical thinking skills could be measured proportionally. The assessment of student answers was carried out using a scoring rubric developed based on each of these indicators. The detailed scoring rubric is presented in Table 2. Each student answer was given a score ranging from 0 to 4, where a score of 4 indicated the highest level of achievement for each indicator. Thus, the maximum score for all essay questions was 20. This score was then converted to a scale of 0–100 for further analysis. In this study, the assessment was conducted by a single rater, namely the researcher. To maintain consistency in the scoring process, each student's answer was strictly evaluated based on the criteria established in the rubric, so that all assessments were carried out consistently according to the same indicators. Furthermore, the pretest and posttest scores of the experimental class and the control class were compared to analyze the effect of the treatment on students' critical thinking skills. The results of the descriptive statistical analysis of these data are presented in Table 10.

Table 10. Descriptive statistics of test data**.**

Class	Mean	Std. Deviation
Experimental Pretest	43.61	10.994
Experimental Posttest	64.86	12.789
Control Pretest	42.36	10.986
Control Posttest	54.72	11.829

As presented in Table 10, the average pretest score of the experimental class was 43.61, while that of the control class was 42.36. These results indicate that the initial abilities of students in both classes were relatively not far apart before the treatment was given. After the treatment was administered, the average posttest score of the experimental class increased to 64.86, while the control class obtained an average of 54.72. The increase in posttest scores in the experimental class indicates that the implemented learning was more effective in improving students' critical thinking skills compared to the learning in the control class.

A normality test was conducted to evaluate the distribution of pretest and posttest scores among both groups, focusing on students' critical thinking skills before proceeding with additional statistical analysis. The assessed data comprised pretest and posttest results obtained from the experimental as well as the control groups. Each group included 36 students, and the Shapiro-Wilk test was applied using SPSS to confirm that the data met the requirements for parametric testing. The findings of the normality test regarding students' critical thinking skills are displayed in Table 11.

Table 11. Normality test results of students' critical thinking skills data

Class	Shapiro-Wilk		
	Statistic	df	Sig.
Control Class Pretest	.950	36	.107
Control Class Posttest	.954	36	.137
Experimental Class Pretest	.957	36	.180
Experimental Class Postest	.960	36	.220

As shown in Table 11, all significance values in this study were greater than 0.05 for both the pretest and posttest in the experimental and control groups. The significance value for the pretest in the control group was 0.107, while the posttest value was 0.137. In the experimental group, the significance value for the pretest was 0.180 and for the posttest was 0.220. These values indicate that the data in each group did not deviate significantly from a normal distribution. Therefore, the data met the assumption of normality, making them suitable for hypothesis testing and further analysis.

The results of the homogeneity test for students' critical thinking abilities data

The next step after verifying that the data on students' critical thinking abilities followed a normal distribution was to conduct a homogeneity test for variances. The goal of conducting this test was to find out if both the experimental and control groups exhibited an equal extent of variability. Levene's Test was used through the Test of Homogeneity of Variances option in SPSS to run the test. The outcomes of the homogeneity test for students' critical thinking skills are shown in Table 12.

Table 12. The Results of homogeneity test of variances of students' critical thinking skill

Test of Homogeneity of Variance	Levene Statistic	df1	df2	Sig.
Based on Mean	.065	1	70	.799

As shown in Table 12, the results of the homogeneity of variance test using the Levene Test based on the mean yielded a significance value of 0.799. This value is greater than 0.05, so it can be concluded that the variances of the data between the experimental class and the control class are homogeneous or have equal variances. Thus, the homogeneity assumption in parametric statistical testing has been met, allowing data analysis to proceed to the hypothesis testing stage.

Because the pretest scores between the experimental class and the control class were relatively not far apart, as presented in Table 10, and the data were normally distributed and homogeneous, an independent sample t-test was conducted to compare the posttest scores between the experimental class and the control class. This test aimed to determine whether there was a significant difference in students' critical thinking skills after the two classes received different learning treatments. The results of the hypothesis test are presented in Table 13.

Table 13. The Results of Independent Sample t-test on Students' Critical Thinking Skills

Description	t	df	Sig. (2-tailed)	Mean Difference	95% CI Lowe	95% CI Upper
Equal variances assumed	-3,49	70	0.001	-10.139	-15.930	-4.348
Equal variances not assumed	-3,49	69.6	0.001	-10.139	-15.930	-4.348

Based on Table 13, a significance value (Sig. 2-tailed) of 0.001 was obtained, which is less than 0.05. This result indicates that there is a significant difference in students' critical thinking skills between the experimental class and the control class. The experimental class, which received learning using the Problem Based Learning (PBL) assisted by Liveworksheet, showed better posttest results compared to the control class. Thus, the research hypothesis is accepted.

The outcomes of Cohen's effect analysis of effect size estimation

The effect of the Problem Based Learning (PBL) assisted by the Liveworksheet application on students' critical thinking skills was analyzed using Cohen's effect size based on the posttest scores of the experimental class and the control class. The effect size analysis was conducted to determine the magnitude of the difference in final learning outcomes between the two groups after receiving different learning treatments, while the improvement in students' abilities from pretest to posttest was further analyzed using N-Gain scores in both classes. The results of the effect size analysis are presented in Table 14.

Table 14. Description of posttest scores and effect size of critical thinking skills

Cohen's Effect Size Estimation Test			
Critical Tinking Skills			
Class	N	Mean	Std. Deviation
Control Class Posttest	36	54.72	11.829
Experimental Class Posttets	36	64.86	12.789
Effect Size Value	0,83		
Category	High		

Based on the results of the Cohen

analysis, an effect size value of 0.83 was obtained, which falls into the high category according to the criteria in Table 7. This result indicates that the posttest scores of students in the experimental class differed considerably from those in the control class after the implementation of different learning treatments. Meanwhile, the results of the ability improvement analysis using N-Gain scores showed that the experimental class experienced a higher improvement compared to the control class. Thus, the research findings indicate that the implementation of the PBL assisted by Liveworksheet contributes better to the development of students' critical thinking skills in wave material compared to the learning implemented in the control class.

Results of the N-Gain assessment concerning students' critical thinking skills

The N-Gain value was calculated to evaluate the improvement in students' critical thinking skills on wave material after the learning process. The calculation was performed based on the pretest and posttest scores of both groups, namely the experimental class and the control class, to observe the improvement in each group as well as to compare the effectiveness of the learning provided. The results of the N-Gain calculation using SPSS software are presented in Table 15 below.

Table 15. Comparison of N-Gain values of experimental class and control class on students' critical thinking ability

	N	Mean	Std. Deviation
NGain score of experimental class	36	.3655	.22618
NGain percent of experimental class	36	36.548	22.61848
NGain score of control class	36	.2234	.08231
Ngain percent control class	36	22.339	8.23111

The results presented in Table 15 show that the average N-Gain score in the experimental class was 0.3655 (36.55%), while in the control class it was 0.2234 (22.34%). Based on the N-Gain criteria in Table 8, the experimental class fell into the medium category, whereas the control class fell into the low category. This indicates that the improvement in students' critical thinking skills in the experimental class was higher than that in the control class. Thus, it can be inferred that the learning in the experimental class provided a better improvement in students' critical thinking skills on wave material compared to the control class.

As a supplement to the quantitative results, sample student answers are presented in Figure 1 and Figure 2. The student answers displayed were selected as representative examples based on the scoring rubric used in this study. Figure 1 shows a student answer that falls into the appropriate category for the indicator of providing further explanations, while Figure 2 shows a student answer that falls into the less appropriate category because the explanation provided was still incomplete and indicated a misconception regarding wave concepts.

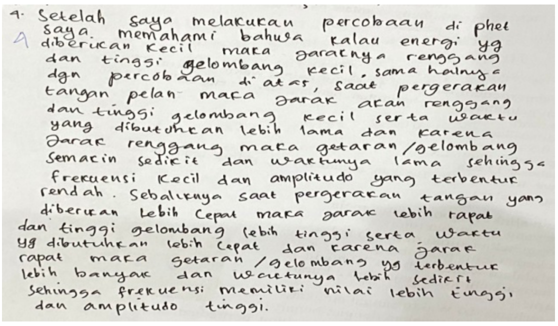
4. Setelah saya melakukan percobaan di phet saya memahami bahwa kalau energi yg diberikan kecil maka jaraknya renggang dan tinggi gelombang kecil, sama halnya dgn percobaan di atas, saat pergerakan tangan pelan maka jarak akan renggang dan tinggi gelombang kecil serta waktu yang dibutuhkan lebih lama dan karena jarak renggang maka getaran/gelombang semakin sedikit dan waktunya lama sehingga frekuensi kecil dan amplitudo yang terbentuk rendah. Sebaliknya saat pergerakan tangan yang diberikan lebih cepat maka jarak lebih rapat dan tinggi gelombang lebih tinggi serta waktu yg dibutuhkan lebih cepat dan karena jarak rapat maka getaran/gelombang yg terbentuk lebih banyak dan waktunya lebih sedikit sehingga frekuensi memiliki nilai lebih tinggi dan amplitudo tinggi.

Figure 1. Student answers in the appropriate category for the indicator of providing further explanations

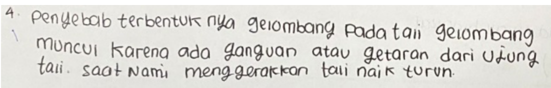
4. Penyebab terbentuknya gelombang pada tali gelombang muncul karena ada gangguan atau getaran dari ujung tali. saat nami menggerakkan tali naik turun.

Figure 2. Student answers in the less appropriate category for the indicator of providing further explanations

According to student feedback, the use of Liveworksheet e-LKPD was instrumental in implementing of PBL

The student response questionnaire consisted of 15 statements administered through the Liveworksheet platform to determine students' reactions to the implementation of the PBL assisted by interactive e-worksheets. This instrument used a Likert scale with a score range of 1 to 5 for each statement. The calculation of student responses was carried out by converting the scores obtained into percentages according to the formula described in the research methods section.

Table 16. Recapitulation results of students response questionnaire

Indicator	Percentage	Criteria
Enjoyment	88%	Very Good
Interest	84%	Very Good
Attention	88%	Very Good
Engagement	78%	Good
Outcome	85%	Very Good

Based on Table 16, the average percentage of student responses was 85%, which falls into the very good category. This indicates that students gave positive responses to the learning process using the Problem Based Learning (PBL) assisted by Liveworksheet-based e-worksheets.

DISCUSSION

The improvement in students' critical thinking skills in the experimental class can be attributed to the characteristics of the Problem Based Learning (PBL), which encourages students to identify problems, analyze information, evaluate evidence, and formulate solutions based on scientific reasoning. In wave material, students were trained to analyze the relationships among wavelength, frequency, period, amplitude, and wave speed through problem-solving activities integrated into the interactive Liveworksheet-based e-worksheet. The use of PhET simulations in both classes helped students visualize abstract concepts in wave material. However, in the experimental class, the simulations were integrated with interactive e-worksheets and a more structured PBL, making the concept exploration process more systematic. Students not only observed the simulations but were also guided to analyze phenomena, connect wave variables, and construct explanations based on their observations. The dynamic visualization in PhET simulations helped students understand the relationships among frequency, wavelength, amplitude, and wave speed, which were previously difficult to comprehend through static images. Furthermore, the use of simulations also helped reduce student misconceptions, particularly in understanding the relationship between frequency and wavelength as well as the effect of source vibration on the resulting wave pattern. The difference in the quality of student answers shown in Figure 1 and Figure 2 demonstrates that students in the experimental class were able to provide more logical, complete, and conceptually accurate explanations of wave concepts compared to students in the control class. In contrast, some students in the control class still showed difficulties in connecting wave concepts scientifically, so their explanations were not entirely accurate.

This finding supports the research conducted by Al-Farisi et al., (2023), which demonstrates that employing PBL media enhances students' advanced thinking skills by fostering a more effective educational experience. Additionally, the study by Fajarna et al., (2025) reveals that the problem-based learning method can greatly improve students' critical thinking skills through the processes of analyzing and resolving issues. The notable difference between the experimental and control groups arises from the distinctive characteristics of their learning techniques. In the experimental group, the PBL method encourages students to engage actively in problem-solving, involving steps such as identifying issues, gathering relevant information, and drawing conclusions. This strategy effectively develops critical thinking abilities, including analysis, evaluation, and conclusion formulation. Moreover, the integration of interactive Liveworksheet based e-LKPD with PhET simulations allows students to transform abstract concepts about waves into more tangible representations. This facilitates learners' understanding of the interconnections between various concepts, resulting in more systematic and logically scientific responses. Conversely, the instructional strategies employed in the control group have not adequately inspired students to engage fully in the problem solving process, leading to limited advancement in their higher-order thinking skill development.

The effect size calculations corroborate the earlier findings regarding the potential benefits of implementing the learning. The effect size measurement is 0.83, which is regarded as high, as seen in Table 9. The fact that this amount is so high suggests that the PBL paradigm, along with Liveworksheet, is a significant aid in enhancing students' critical thinking abilities. This magnitude of effect size not only establishes statistical significance but also demonstrates a significant advancement in learning techniques. This claim is supported by Kamal et al., (2024) research, which shows that the PBL approach in physics instruction had an effect size of 2.191, placing it in a very high range and indicating a significant impact on students' critical thinking skills. Additionally, these results are consistent with Su et al., (2025), who performed a meta-analysis and discovered that the PBL consistently improves students' critical thinking abilities, with an effect size of 0.98.

Table 15 shows that the average N-Gain score in the experimental class was 0.3655, which falls into the medium category, while the control class obtained an average N-Gain score of 0.2234, which falls into the low category. These results indicate that the improvement in students' critical thinking skills in the experimental class was higher than that in the control class after the implementation of learning using the Problem Based Learning (PBL) assisted by interactive Liveworksheet-based e-worksheets. Although the improvement in the experimental class has not yet reached the high category, the results of this study indicate a development in students' critical thinking skills after learning. This is supported by the student answers shown in Figures 1 and 2. Students in the experimental class tended to be able to provide more complete and logical explanations on wave material. Based on the student answer in Figure 1, students were able to explain the relationships among frequency, wavelength, amplitude, and wave speed based on observations made through PhET simulations. Students were also able to explain that changes in frequency affect the wavelength and the resulting wave pattern. In contrast, some students in the control class still showed incomplete explanations and were unable to accurately connect the relationships among wave variables, so their reasoning remained limited to simple descriptions of the observed phenomena. Furthermore, the results of the student response questionnaire in Table 16 showed a response percentage of 85% in the very good category. This indicates that students gave positive responses to learning using the PBL assisted by Liveworksheet-based e-worksheets. These positive responses suggest that the use of interactive learning helped students become more active in understanding wave concepts, although some students still needed adjustment in following problem-based learning and using interactive media. These findings are in line with the research by Lee, (2025), which stated that the improvement in student learning outcomes in the implementation of a new learning model is often not yet optimal at the initial stage because students are still adapting to a learning process that differs from conventional instruction. Furthermore, Yu & Zin (2023) also explained that students' ability to engage in technology-based and problem-based learning will develop gradually as students gain more experience in using the learning model.

In this study, the implemented learning showed an effect on students' critical thinking skills, as indicated by an effect size value of 0.83, which is classified as high, and an N-Gain value in the experimental class of 0.3655, which falls into the medium category. The high effect size value indicates a considerable difference in final critical thinking skills outcomes between the experimental class and the control class after the implementation of different learning treatments. Meanwhile, the medium-category N-Gain value indicates that the improvement in students' critical thinking skills in the experimental class still occurred gradually and had not yet reached the high category. The difference between the high effect size value and the medium N-Gain can be understood because these two analyses measure different aspects. Effect size is used to examine the magnitude of the difference in posttest results between the experimental class and the control class, whereas N-Gain is used to measure the level of improvement in students' abilities from their initial condition before learning to after learning. In this study, students in the experimental class achieved better posttest results compared to the control class, but the improvement in students' critical thinking skills still required an adaptation process to problem-based learning and the use of interactive media. This is supported by the results of student answers and student responses during learning. Based on the student answers in Figures 1 and 2, some students still experienced difficulties in connecting wave concepts scientifically, particularly in explaining the relationships among frequency, wavelength, amplitude, and wave speed. Nevertheless, students in the experimental class were already able to provide more logical and complete explanations compared to students in the control class. Furthermore, the results of the student response questionnaire in Table 16, which showed a percentage of 85% in the very good category, indicate that students gave positive responses to the use of the PBL assisted by Liveworksheet-based e-worksheets. This finding is in line with the research by Nurillahi et al (2024), which stated that a learning model can show a large effect based on effect size values, but the improvement in learning outcomes measured using N-Gain is not always in the high category. This condition can occur because students need time to adapt to problem-based learning, critical reasoning, and the use of interactive learning media, so that the development of critical thinking skills takes place gradually.

The analysis of student responses in Table 16 shows that the average percentage of student responses reached 85% in the very good category. This result indicates that students gave positive responses to learning using the Problem Based Learning (PBL) assisted by Liveworksheet-based e-worksheets. The characteristics of the PBL, which encourage active student engagement through problem-solving activities and the use of interactive media, help create a more engaging learning process and encourage student participation during the learning session. Furthermore, the use of Liveworksheet-based e-worksheets helps students learn abstract concepts in wave material in a more concrete and visual manner through structured learning activities. This finding is supported by the research of Ulfaa et al. (2025), which stated that the use of interactive digital learning media in a problem-based learning can increase student motivation and engagement in learning. Furthermore, Dewi & Nisa' (2025) also explained that the use of the PBL assisted by interactive media can create a more engaging learning atmosphere and help students understand the material better.

Nevertheless, the results of student responses in this study need to be interpreted cautiously because the data were obtained through self-report questionnaires, so student answers were highly dependent on each individual's perception during learning. Furthermore, the high level of positive student responses may also be influenced by the novelty effect of using interactive digital media based on Liveworksheet, which had never been used before in physics learning. This study also did not compare student responses between the experimental class and the control class, so differences in perceptions between the two groups could not be analyzed in greater depth. Therefore, future research could develop student response analysis by involving comparisons between groups and using observational or interview data to obtain a more comprehensive picture of students' learning experiences.

CONCLUSION

This study employed a quasi-experimental design to examine the effect of integrating the Problem Based Learning (PBL) with interactive e-worksheets based on the Liveworksheet platform and PhET simulations on wave material on students' critical thinking skills. The results showed that this learning approach had a considerable effect on students' critical thinking skills, as indicated by an effect size value of 0.83. Furthermore, the improvement in students' critical thinking skills was in medium category, based on N-Gain value of 0.3655. Student responses to the learning process were also classified as positive, with an agreement level of 85%. Nevertheless, the results of this study need to be interpreted cautiously due to several limitations, namely the use of a quasi-experimental design and a sample limited to one school, so the generalization of the research findings remains limited. Therefore, further research involving a broader sample and a stronger experimental design, such as randomization or studies conducted across multiple schools, is needed to strengthen the external validity of the findings. In addition, further investigation is also recommended to examine the effectiveness of this learning model on other physics topics in different learning contexts.

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