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The effect of using PBL-STEM-based worksheets on students' critical thinking skills in Biotechnology

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ABSTRACT

Critical thinking is an essential competency in science education that must be systematically developed. However, biology instruction remains predominantly teacher-centered and lacks learning resources that actively engage students in higher-order thinking. One promising approach is the use of Problem-Based Learning (PBL)-STEM-based worksheets, which integrate authentic problem-solving with interdisciplinary STEM concepts to promote meaningful and contextual learning. This research focused on assessing the effectiveness of PBL-STEM-based worksheets in enhancing students' critical thinking skills during biotechnology instruction at MAS Al-Washliyah Kedaisianam. A quasi-experimental method with a pretest-posttest control group design was employed. The sample consisted of 58 students selected through purposive sampling, with 29 students in the experimental class (X IPA-1) and 29 students in the control class (X IPA-2). Data were collected using five essay questions developed based on Ennis's critical thinking indicators. Statistical analyses included the Shapiro-Wilk normality test, Levene's test for homogeneity of variances, and the independent samples t-test using IBM SPSS Statistics version 25. The findings revealed that the experimental group's mean score increased from 50.69 on the pre-test to 72.07 on the post-test, whereas the control group's mean score improved from 50.00 to 63.28. The independent samples t-test produced a significance value of 0.008 (p < 0.05), indicating a statistically significant difference between the two groups. These results demonstrate that PBL-STEM-based worksheets significantly improve students' critical thinking skills in biotechnology. Therefore, integrating PBL and STEM through structured worksheets provides an effective instructional strategy for fostering active, inquiry-based, and critical learning in biology classrooms.

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INTRODUCTION

Education in the 21st century requires students not only to understand concepts but also to think critically when facing various problems. Critical thinking is an essential competency in science education, particularly in biology, as it enables students to analyze problems, evaluate information, and draw conclusions based on scientific evidence (Kasanah et al., 2026). Globally, strengthening this ability is viewed as a primary goal of science education that must be achieved systematically through the use of appropriate learning tools, one of which is the Student Worksheet (Galaze, 2025).

The use of the Problem-Based Learning (PBL) model and the Science, Technology, Engineering, and Mathematics (STEM) approach in learning materials has received significant attention in the international literature due to their effectiveness in fostering active thinking and real-world problem-solving (Simanjuntak & Purwaningsih, 2024). Ennis states that critical thinking encompasses the ability to provide explanations, develop foundational skills, draw conclusions, and manage thinking strategies (Santia & Hidayati, 2024). This indicates that learning must be designed to systematically activate students' thinking processes so they can adapt to changes and advancements in scientific knowledge.

These abilities, within the context of biology instruction on biotechnology topics, hold great potential for development. Biotechnology topics relate to real-world phenomena and modern scientific issues (Ashokumar, 2023). Topics such as genetic engineering, tissue culture, and biotechnology production require students to do more than memorize concepts. Students must also understand concepts in depth and apply them practically (Endang et al., 2021). A biotechnology curriculum based on practical activities and inquiry has also been shown to deepen students' biological understanding in a more meaningful way (Cooper et al., 2019). This indicates that the learning approach must be able to connect concepts to real-world problems.

Such a learning approach can be supported through structured worksheets. Worksheets can help students engage in a more focused learning process (Sani & Ambarwati, 2024). The effectiveness of worksheets depends heavily on the design and approach used in instruction. Using the PBL model in this learning process places students in real-world problem-solving situations (Sani & Ambarwati, 2024). This approach encourages students to actively investigate the problems presented (Ayunda et al., 2023). In the context of biology instruction, the PBL model has been shown to have a significant effect size on improving students' critical thinking skills compared to conventional teaching models (Supratman et al., 2021). This learning process helps students systematically develop their critical thinking skills (Harahap et al., 2023). In addition, students are also trained to discuss and collaborate in finding solutions (Nurfadhila et al., 2024).

In this approach, the STEM approach integrates science, technology, engineering, and mathematics into the learning process to support students' more comprehensive understanding (Ichsan et al., 2023). This approach encourages students to develop critical thinking and problem-solving skills (Fithri et al., 2021). The learning process connects concepts with their real-life applications, making the learning more meaningful (Ashokumar, 2023). This integration helps students understand the material contextually and practically (Milala et al., 2024). Problem-based learning activities in the fields of science and technology have been shown to facilitate conceptual change and improve students' inquiry skills (Valsecchi et al., 2023). Combining PBL and STEM in worksheets can serve as an alternative to enhance students' critical thinking skills.

Implementing this teaching approach in the classroom still faces various challenges. Classroom conditions indicate that students' critical thinking skills remain relatively low. The 2022 PISA results ranked Indonesia 68th out of 81 countries in science literacy (OECD, 2023). Interviews with biology teachers at MAS Al-Washliyah Kedaisianam revealed that instruction is still dominated by lecture-based methods, a finding supported by a pre-assessment questionnaire indicating students' low critical thinking skills. The worksheets used remain conventional and do not yet encourage students to engage in critical thinking. Students tend to merely memorize material without developing analytical and evaluative skills (Prasetya et al., 2024; Sari et al., 2019).

This situation has been a focus of various previous studies. Prior research indicates that the PBL model and the STEM approach can enhance students' critical thinking skills. Empirically, the STEM approach integrated into the biology curriculum, including genetics, has been shown to improve all sub-skills of critical thinking among high school students, yielding statistically significant results (Yaki, 2022). Furthermore, a study (Pertiwi et al., 2024) states that STEM-based learning media combined with the Problem-Based Contextual Learning model has been proven effective in enhancing students' critical thinking skills through contextual and technology-based learning experiences. The integration of STEM and inquiry in biology instruction also directly influences students' critical thinking skills and conceptual mastery simultaneously (Zakiyah et al., 2021).

Findings from recent international research demonstrate that integrating PBL-STEM into learning significantly supports conceptual change by involving students in authentic problem-solving activities, particularly in comprehending the characteristics of protein molecules (Valsecchi et al., 2023) and tackling current and complex biological challenges (Meesamran & Polyiem, 2024). However, most existing studies examine PBL or STEM models separately. Research that integrates these two concepts into worksheets, particularly for biotechnology topics, remains scarce (Hasanah et al., 2021; Milala et al., 2024). In fact, this kind of interdisciplinary combination is extremely important, as group collaboration in solving scientific problems in the biotechnology sector is a cornerstone of science education today (Cascella & Jez, 2016). Research on biotechnology topics also tends to focus more on product development than on assessing critical thinking skills (Nurfadhila et al., 2024). These issues indicate an opportunity for more integrated research. The main difference between this study and previous research is the use of PBL-STEM-based worksheets specifically designed for biotechnology content, with a focus on strengthening critical analysis skills rather than merely technical understanding of products.

Based on these issues, this study aims to analyze the effect of using PBL-STEM-based worksheets on students' critical thinking skills. These worksheets are designed to help students solve problems systematically during the learning process. The STEM approach is used to integrate various scientific aspects into the learning process. These worksheets are expected to enhance students' critical thinking skills. The results of this study are expected to contribute to the development of more innovative biology instruction.

METHOD

This study is quantitative in nature, employing a quasi-experimental method with a pretest-posttest control group design. Both groups were administered a pretest before the intervention and a posttest after the intervention, conducted at Mas Al-Washliyah Kedaisianam in March 2026. This institution was selected because it represented the actual phenomenon of low use of innovative instructional media and students' suboptimal critical thinking skills, making it a relevant setting for testing the efficacy of PBL-STEM-based worksheets. The population in this study consisted of 169 students from five 10th-grade science (IPA) classes. Purposive sampling was used to select 10th-grade science class IPA-1 (29 students) as the experimental class and 10th-grade science class IPA-2

(29 students) as the control class, for a total sample size of 58 students. The purposive sampling technique was chosen because the quasi-experimental design utilizes pre-existing classes (intact groups), so the sample was determined based on specific considerations rather than individual randomization (Sugiyono, 2022). Classes X IPA-1 and X IPA-2 were selected from the five existing X IPA classes because the same teacher taught them, had comparable initial academic achievement levels, and followed the same class schedule. All students in both classes were included as the sample; thus, the 58 students constituted the accessible population rather than a result of sample size calculations.

This study consisted of three stages: preparation, implementation, and completion. The preparation stage began with field observations to identify gaps in critical thinking skills, followed by the selection of subjects using a sampling technique based on the school's specific needs. In this stage, instructional materials in the form of PBL-STEM-based modules and worksheets were developed, along with an assessment instrument consisting of five essay questions. To ensure content validity, these instruments were validated by test experts to confirm that each item aligned with the targeted critical thinking skills. During the implementation stage, a pre-test was administered to assess students' initial abilities before the intervention. Instruction in the experimental class was conducted by applying PBL steps within a STEM framework to biotechnology material. This process required students to identify the problem, organize group investigations, present solutions to real-world problems, and engage in reflection and evaluation after the learning process. The completion stage focused on final assessment through a post-test and the analysis of research data.

The data collection method utilized five critical thinking essay questions based on Ennis's indicators, which include: providing a simple explanation, building basic skills, drawing conclusions, providing an advanced explanation, and formulating strategies and tactics. Teachers and students used observation sheets to review teaching activities and the learning process. Data analysis was conducted using a normality test *(Shapiro-Wilk)* and a homogeneity test *(Levene's Test),* followed by an independent-samples t-test *(Independent Sample T-Test)* followed by an independent samples t-test at a 5% significance level (95% confidence interval) using IBM SPSS Statistics version 25, with the criteria that (H_0) is rejected and (H_1) accepted if the significance value ($p < 0.05$), indicating that the use of PBL-STEM-based worksheets has a significant effect on students' critical thinking skills (Cresswell & Cresswell, 2018).

RESULTS AND DISCUSSION

Before conducting the experimental phase, the researcher first developed learning materials in the form of PBL-STEM-based worksheets as the main component of the instructional intervention. To ensure the suitability and readability of these materials before implementing them in the pilot test, the worksheets first underwent a validation process by media experts and subject matter experts. Based on the assessment findings and suggestions for improvement provided by the validators, the researcher then carried out a series of content revisions. Details regarding the validators' comments comparing the worksheets' appearance before and after the revision process are comprehensively presented in Table 1 below.

Table 1. Comments from media validators and content validators

Suggestions	Before revision	After revision
Insert a set of prompt questions in the lower right corner of the tempeh material page to stimulate students' critical analysis skills		
Integrate a column of prompt questions in the upper right corner of the yogurt and cheese product material sheets		
Present the topic of bioremediation as a concrete example of the application of conventional biotechnology in the environmental sector.		
Including a theoretical review of the positive and negative implications of biotechnology use in the agricultural sector, and inserting critical thinking prompts on the page containing the vaccine material.		

(Source: Researcher, 2026)

This material has been carefully designed to align with the learning objectives for the biotechnology topic and has undergone expert validation to ensure its quality and suitability. The results of the material validation are presented in the following Table 2.

Table 2. Results of expert validation of the instrument

Validator	Percentage (%)	Criteria
Media Expert Validator	78.12%	Acceptable
Content Expert Validator	85.41%	Highly Acceptable

(Source: Sugiyono, 2022)

Based on the validation results in Table 2, the LKPD media is deemed suitable for use in learning. In addition to media validation, the critical thinking skills test instrument, consisting of five essay questions, has also undergone validation by instrument experts. The expert validation results for each question are presented in Table 3 below.

Table 3. Validation results for critical thinking test questions

Question No.	Critical Thinking Indicator (Ennis)	Biotechnology Topic	Percentage (%)	Criteria
Question 1	Providing a Simple Explanation (*Elementary Clarification)*	Protease enzymes in tempeh	87.50%	Highly Acceptable
Question 2	Building Basic Skills (*Basic Support)*	Failure of yogurt milk pasteurization	75.00%	Acceptable
Question 3	Drawing Conclusions (*Inference)*	Accuracy of salt content in soy sauce	84.38%	Very Acceptable
Question 4	Providing Further Explanation (*Advanced Clarification)*	*Freeze-Drying* vs. *Onggi* Kimchi Jars	78.12%	Acceptable
Question 5	Setting Strategies and Tactics (*Strategy and Tactics)*	Solution to the tempeh incubator temperature crisis	87.50%	Very Acceptable

(Source: Researcher, 2026)

Next, Table 4 presents the pre-test and post-test results for critical thinking skills as follows.

Table 4. Pre-test and post-test results for the experimental class

Statistic	Pre-test	Post-test
Mean	50.69	72.07
Standard Deviation	10.833	13.398
Minimum Value	25	35
Highest Value	75	95

(Source: Researcher, 2026)

Descriptive statistics for the experimental class show that students' pre-test scores were relatively low, with an average of 50.69. After the learning process using PBL-STEM-based worksheets, post-test scores increased significantly to 72.07. The distribution of values for the experimental class can be seen in Figure 1.

Figure 1 for the experimental class shows that the distribution of pre-test and post-test scores is concentrated in the 41–55 range, indicating that the students' initial abilities were relatively low and homogeneous. After the intervention, post-test scores shifted significantly to a higher range, with the majority of scores falling between 71 and 85. Only a few students scored below 60, indicating the effectiveness of PBL-STEM-based worksheets in improving critical thinking skills across the board.

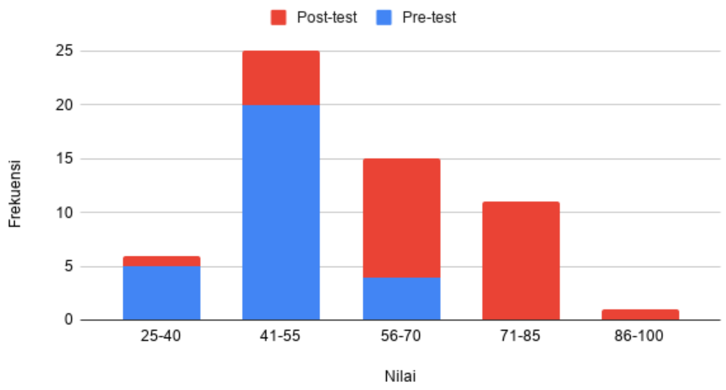

Figure 1. Distribution of pre-test and post-test scores in the experimental class

Meanwhile, in Table 5, the pre-test and post-test results for the control class, which used conventional teaching methods, showed an average increase from 50 to 63.28. However, this increase was not as significant as that observed in the experimental class. Furthermore, the lowest post-test score remained low at 45, indicating that the conventional learning method has an uneven impact on student achievement. The following figure shows the distribution of scores for the control class:

Table 5. Pre-test and Post-test Results for the Control Class

Statistic	Pre-test	Post-test
Mean	50.00	63.28
Standard Deviation	12.247	10.961
Minimum Value	25	45
Highest Value	75	80

(Source: Researcher, 2026)

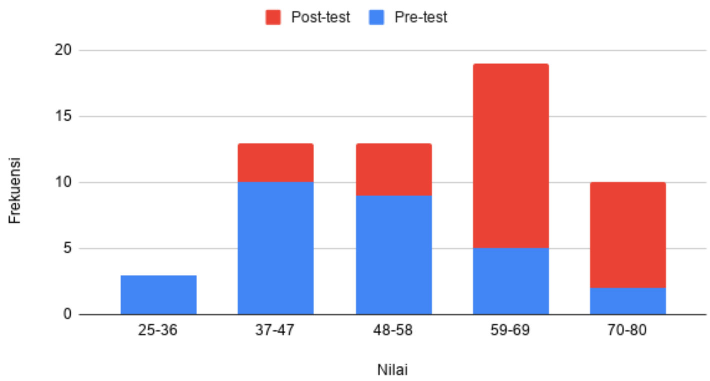

Figure 2. Distribution of pre-test and post-test scores for the control class

Figure 2 shows the score distribution of students who used conventional learning methods without any specific model intervention. Most scores fell within the 37–50 range, indicating that their initial abilities were comparable to those of the experimental class. After the learning process, post-test scores were more widely distributed between 59 and 69. Some students still scored below 60, indicating that conventional learning is less effective in improving students' critical thinking skills uniformly.

The following figure compares critical thinking scores between the experimental and control classes:

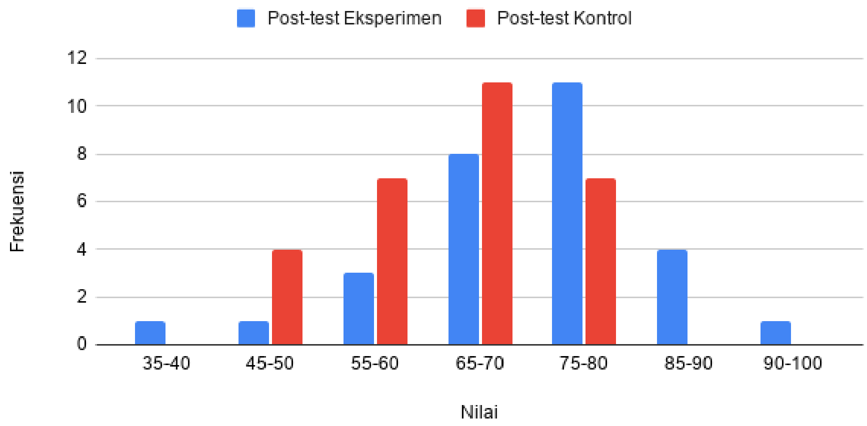

Figure 3. Comparison of post-test score distributions in the experimental and control classes

The comparison between the two classes is clearer in the following figure. The figure above compares the distribution of post-test scores between the experimental and control classes. In the experimental class, scores were highly concentrated in the 75–80 range, reflecting the effectiveness of PBL-STEM-based worksheets in improving student learning outcomes. In contrast, the control class shows a broader and lower distribution, with most scores falling in the 60–70 range, and some scores below 60. This visual comparison demonstrates that PBL-STEM-based worksheets are superior in enhancing students' critical thinking skills compared to conventional teaching methods.

This study is quantitative; therefore, normality and homogeneity tests were used. Before conducting hypothesis testing, prerequisite tests—including normality and homogeneity tests—were first performed. The normality test was conducted to determine whether the critical thinking ability data in the experimental and control classes were normally distributed. This test used the Shapiro-Wilk test because the sample size in each group was less than 50 students. After data processing in SPSS was completed, the results of the normality test are presented in Table 6.

Table 6. Normality test

	Experimental Class	**Control Class**
	Pre-Test	
Shapiro-Wilk Sig.	0.625	0.842
Category	Normally distributed	Normally distributed
	Post-Test	
Shapiro-Wilk Sig.	0.341	0.121
Category	Normally distributed	Normally distributed

(Source: SPSS 25.0)

Based on the table above, the *Shapiro-Wilk* normality test using IBM SPSS Statistics version 25 software shows that the pre-test and post-test data for both groups have significance values above 0.05. In the experimental class, the significance value for the pre-test was 0.625 and for the post-test

0.341. Similarly, in the control class, the significance value for the pre-test was 0.842 and for the post-test 0.121. Since all significance values were greater than the α level of 0.05, it can be concluded that the data from both groups are normally distributed.

After confirming normality, a homogeneity test was conducted. The homogeneity test was performed to determine whether the variances in critical thinking ability between the experimental and control classes were equal (homogeneous). The test used was Levene's test for the equality of two variances, as shown below:

Table 7. Homogeneity test of students' critical thinking skills

Students' Critical Thinking Skills	Statistics	df1	df2	Sig.
Based on the mean	0.655	1	56	0.422
Based on the median	0.614	1	56	0.437
Based on the median (adjusted df)	0.614	1	51.443	0.437
Based on the trimmed mean	0.637	1	56	0.428

(Source: SPSS 25.0)

Based on the table above, the significance value for students' critical thinking skills in the experimental and control classes, based *on* the mean, is 0.422, which indicates that this value is greater than 0.05. It can be concluded that the two classes exhibit identical or homogeneous variation.

Table 8. Hypothesis testing

		Levene's Test for Equality of Variances		t-Test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Standard Error of the Difference	95% confidence interval for the difference	
									Lower	Upper
Post-test Student Score	Equal variances assumed	0.655	0.422	2.736	56	0.008	8.793	3.214	2.354	15.232
	Equal variances not assumed			2.736	53.885	0.008	8.793	3.214	2.348	15.238

(Source: SPSS 25.0)

After the prerequisite tests were met, a hypothesis test was conducted using an independent samples t-test. Table 8 above shows the results of the independent samples t-test for students' critical thinking test scores between the experimental and control groups, with a significance value of 0.008 < 0.05, indicating a significant difference in final test scores between the experimental and control classes. It can be concluded that the null hypothesis (H_0) is rejected and the alternative hypothesis (H_1) is accepted because there is an effect of the treatment using PBL-STEM-based worksheets during instruction compared to conventional instruction.

Based on all the quantitative data presented above, an in-depth discussion is provided below. The results of this study indicate that the use of PBL-STEM-based worksheets has a significant effect on students' critical thinking skills regarding biotechnology material at MAS Al-Washliyah Kedaisianam. The following discussion elaborates on these findings based on test results, inter-class comparisons, and the statistical analyses conducted.

The experimental class showed an average increase from 50.69 on the pre-test to 72.07 on the post-test. This improvement did not occur by chance but is directly related to the learning structure implemented through PBL-STEM-based worksheets. In the learning process, students are presented with contextual problems from the outset and are then encouraged to organize information, conduct investigations, and present their findings systematically (Maha & Manalu, 2025). These stages in the PBL framework gradually train students not merely to accept information but also to analyze, evaluate, and draw conclusions based on evidence (Abarang & Delviany, 2022). Guiding independent and group investigations, as well as presenting problem-solving results, enables students not only to understand concepts theoretically but also to relate them to real-world phenomena in a scientific manner (Nabilatussujaah et al., 2026). The integration of the STEM approach into worksheets reinforces this, as students are required to connect biotechnology concepts with practical aspects of technology and engineering. Research indicates that integrating STEM-based learning effectively strengthens students' conceptual understanding while developing their critical thinking skills (Febril et al., 2023).

The development of this teaching material has had a significant impact by revitalizing classroom learning patterns, shifting from a lecture-dominated approach to active, student-centered learning. Implementing this teaching material has created a more dynamic classroom atmosphere, where students do not merely passively receive information but actively take on the role of *problem solvers*. This shift has led to multi-directional interactions and the practical application of science literacy within biotechnology content, making the learning process more meaningful and applicable for students at MAS Al-Washliyah Kedaisianam.

In the control class, which employed conventional teaching methods, the average post-test score reached only 63.28, an increase from 50.00 on the pre-test. Although there was an improvement, this figure fell far short of the experimental class's achievement. This limited improvement is understandable, given that conventional teaching tends to position students as passive recipients of information, with little room to develop independent analytical and evaluative skills (Firdausi et al., 2023). The low level of students' critical thinking skills in biology learning is partly due to the lack of variety in the methods used by teachers and the scarcity of learning media that encourage active thinking on the part of students (Hulu et al., 2024). This situation is also reflected in the control class's lowest post-test score, which remained at 45, indicating that not all students benefited equally from conventional learning.

Differences in achievement between the two classes were also evident in the results for each critical thinking indicator according to Ennis. Overall, the experimental class outperformed the control class on all five indicators, with the highest achievement on the "developing strategies and tactics" indicator (82.76%). Conversely, the control class showed the lowest achievement on the "building basic skills" indicator (51.72%), indicating that students' ability to construct basic arguments remains weak when they do not receive guidance through a learning model that stimulates active engagement. A comparison of performance across these indicators in both sets of data confirms the experimental class's superiority on all critical thinking indicators. This superiority is closely tied to the learning media used in the instructional process; students were guided to solve real

-world problems rather than merely sitting and listening to the teacher's explanations, so indicators requiring higher-order reasoning were most frequently utilized during learning activities. Students' scores on each indicator resulted from a lengthy process within the PBL stages, ranging from identifying problems and researching information to formulating and presenting solutions in front of the class (Hasanah et al., 2023). Findings from previous research also demonstrate that all critical thinking indicators—including strategies and tactics—showed a significant increase after students participated in learning using this model compared to before the intervention (Wardani, 2023).

In contrast, in the control class, the learning process was one-way. The teacher explained, and students took notes and memorized. Students' ability to process what they learned on their own did not develop much, as evidenced by low scores on nearly all indicators, particularly in building basic skills, which reached only 51.72%. Students accustomed to learning in this manner tend to struggle when faced with problems that require them to reason beyond what has been taught (Adrillian & Munahefi, 2024). This is further supported by research findings that conclude that students' low critical thinking skills in science generally stem from teaching models that do not allow students to actively engage in the thinking process (Rahmawati et al., 2024).

There is a fundamental difference between the learning materials developed in this study and existing biotechnology learning materials or those commonly used in schools. While conventional worksheets generally focus only on conveying concepts through summaries of material and rote-memorization questions, these materials specifically integrate elements of technology and engineering into biotechnology content. This learning material requires students to design mathematically quantifiable technical solutions to biotechnology problems, indicating that PBL-STEM-based worksheets are not only effective at raising average scores but also provide a more equitable impact across all students. The implementation of PBL-STEM-based worksheets has been shown to significantly improve students' critical thinking skills (Wandari et al., 2024).

Based on the Independent Sample T-Test, a significance value of 0.008 was obtained, which is below the α level of 0.05; therefore, H_0 is rejected, and H_1 is accepted. These findings indicate that PBL-STEM-based worksheets have a significant positive effect on students' critical thinking skills. This result reinforces the conclusion that the difference in outcomes between the two classes is not merely random variation but a direct result of the treatment administered (Sado et al., 2020). The increase in the average critical thinking ability score from the moderate category to the high category, with a statistically significant difference ($p < 0.05$), indicates that the PBL model is effective in enhancing students' critical thinking skills (Lestari & Hartono, 2025). In a similar context, a quasi-experimental study of high school students also confirmed that the PBL model has a positive and effective impact on students' critical thinking skills in biology learning (Hasibuan et al., 2024).

The improvement in critical thinking skills in the experimental class was also evident from the results of the student critical thinking skills questionnaire, where the average total score achieved by students reached 83.10% and fell into the "highly critical" category. This indicates that the PBL-STEM approach, supported by engaging worksheets, is capable of creating meaningful learning experiences and stimulating students' higher-order thinking skills. Theoretically, these results align with the view that critical thinking involves the ability to analyze, evaluate, and draw logical and reflective conclusions through real-world problems. The problem-based and science-technology activities in these worksheets successfully encouraged students to develop these skills while fostering their intrinsic motivation and self-efficacy (Hitchcock, 2022).

Thus, it can be concluded that the Problem-Based Learning (PBL) model, supported by STEM-based worksheets, has a significant positive impact on improving students' critical thinking skills in biotechnology. Students taught using this PBL-STEM model achieved significantly higher critical thinking scores compared to the control class. This finding is supported by related research, which has shown that STEM-based PBL substantially boosts students' higher-order thinking skills (Hidayati et al., 2021).

CONCLUSION

Based on the research results and data analysis, it can be concluded that PBL-STEM-based worksheets have a significant impact on improving students' critical thinking skills in biotechnology at MAS Al-Washliyah Kedaisianam. This problem-based learning process encourages students to think analytically, reflectively, and solution-oriented in deeply understanding biotechnology concepts. The success of this intervention has important implications for school policy, encouraging the institutionalization of standardized interdisciplinary teaching modules and generating broader social impacts through the emergence of a younger generation equipped with adaptive science literacy to address biotechnology issues in society. As a step toward further development, future research is recommended to expand the sample scope to various educational institutions with heterogeneous demographic characteristics to comprehensively test the efficacy of this medium, as well as to explore other 21st-century variables, such as collaboration skills and creative thinking.

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