



The Effect of Project-Based Learning (PjBL) with STEM Approach on Students' Metacognitive Awareness, Conceptual Understanding, and Biology Problem-Solving Ability

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Abstract: This study aims to analyze effect of the Project-Based Learning model based on the STEM approach on metacognitive awareness, conceptual understanding, and biology problem-solving abilities of grade XI students of SMA Negeri 13 Bone. The novelty of this study lies in integration of PjBL-STEM which simultaneously measures three high-level cognitive aspects in one experimental design. This study is a quasi-experimental study with a Pretest-Posttest Nonequivalent Control Group Design. The sample consisted of two classes (n=72) using a purposive sampling technique. Instruments included the MAI questionnaire, an essay test based on the SOLO taxonomy (prestructural to expanded abstract), and a problem-solving test based on Polya's stages, all of which have met high validity and reliability. Data were analyzed using ANCOVA ($\alpha = 0.05$). The results showed that PjBL-STEM had a significant effect on metacognitive awareness ($p=.004$), conceptual understanding ($p=.01$), and biology problem-solving ability ($p<.001$). The experimental group showed a higher average increase compared to the control, indicating the effectiveness of PjBL-STEM in enhancing systematic and reflective thinking to support development of 21st century skills. Limitations of this study include quasi-experimental design without full randomization and sample size limited to one school. Further research is needed to test the generalizability of the findings.

Keywords: Biology Problem-Solving; Conceptual Understanding; Metacognitive Awareness; Project-Based Learning; STEM.

Introduction

The development of 21st-century science and technology demands innovative, adaptive, and student-centered learning, with an emphasis on the 4C skills (Critical Thinking, Creativity, Communication, and Collaboration). This aligns with the demands of the Independent Curriculum, which encourages contextual and meaningful learning (Muttaqin & Rizkiyah, 2022). However, the 2022 PISA results show that Indonesian students' scientific literacy remains low, with a score of 383, far below the OECD average for scientific literacy in previous years of 485 (OECD, 2023). This condition reflects weaknesses in students' basic skills, including metacognitive awareness, conceptual understanding, and problem-solving abilities. In biology learning, these

weaknesses are particularly evident as students tend to memorize concepts rather than understand them deeply and experience difficulty solving problems requiring higher-order thinking skills.

Metacognitive awareness, which plays a role in regulating learning strategies through the processes of planning, monitoring, and evaluating understanding, is still relatively low. This condition results in students being less able to effectively control their learning process and develop meaningful understanding. Metacognitive awareness enables students to determine appropriate strategies, monitor their success, and make adjustments when difficulties arise. Therefore, this ability contributes significantly to improving conceptual understanding and problem-solving skills in biology learning (Ghimire & Mokhtari, 2025).

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One factor contributing to students' low metacognitive awareness is that the learning process emphasizes memorization of material without providing opportunities for students to design learning strategies, monitor understanding, or evaluate their thinking processes (Wardana et al., 2021). As a result, students are not accustomed to assessing their true understanding of a concept, which can lead to difficulties when faced with a problem. Therefore, students need to be aware of their strengths and weaknesses from the outset, as metacognitive awareness can encourage reflection throughout their learning process (Ismarani et al., 2023). Learning approaches dominated by memorization have been shown to be less relevant for building students' metacognitive awareness, because students are not given the space to regulate, monitor, and evaluate their own learning strategies (Tuononen et al., 2023). Conceptual understanding is also weak because learning tends to focus on conveying abstract theories without linking them to real-life phenomena. This results in students simply memorizing information mechanically without connecting it to contextual applications. Yet, the implications of conceptual understanding are crucial for internalizing knowledge and relating it to real life. Abstract concepts, if not connected to everyday reality, cause students to simply memorize information mechanically without in-depth understanding.

This directly impacts poor biology problem-solving skills, as students lack the skills to identify problems, analyze information, or devise strategies for resolution. Low metacognitive awareness makes it difficult for students to reflect on their thinking processes, while weak conceptual understanding makes it difficult for them to relate theory to contextual situations (Kuswara et al., 2024; Maghfur et al., 2026). The combination of these two factors makes students less flexible and less trained in solving complex problems that require critical and creative thinking. This condition shows the need for innovation in learning models that can integrate these three aspects in a more meaningful and relevant way so that students can have good metacognitive awareness, be able to understand learning concepts and have adaptive biology problem-solving skills in accordance with the demands and needs of 21st-century learning.

Based on initial observations and interviews at SMA Negeri 13 Bone, it was found that students' metacognitive awareness, conceptual understanding, and problem-solving skills in biology were still relatively low. This is influenced by learning practices that are still dominated by lecture methods with little variation in discussions, resulting in passive student interaction and a lack of encouragement for critical and reflective thinking skills that support metacognitive

awareness (Pratama et al., 2024). Practical activities are also rarely conducted, depriving students of opportunities to observe, experiment, and directly experience scientific processes.

This situation tends to weaken understanding of biological concepts, as they are acquired more abstractly without any connection to real-world phenomena. Learning that focuses on memorization further exacerbates the situation, as students tend to retain material only for a short time and struggle to explain more complex biological mechanisms. This situation also impacts weak problem-solving skills, as students are not accustomed to analyzing biological problems in depth or seeking alternative solutions based on the concepts they learn. In fact, a good understanding of concepts contributes positively to students' problem-solving abilities (Devi et al., 2025). Furthermore, low student engagement in scientific activities, reflected in limited science process skills, also hinders the development of meaningful understanding. The lack of investigative and experimental activities results in students being less trained in scientific thinking (Aisah & Agustini, 2024). This ultimately results in weak metacognitive awareness, conceptual understanding, and problem-solving skills in biology learning. One potential solution to address these issues is the implementation of a Project-Based Learning model based on a STEM approach (PjBL-STEM). This model not only emphasizes practical conceptual understanding but also encourages students to plan, implement, and evaluate projects collaboratively (Muyassaroh et al., 2022). This model has the potential to develop metacognitive awareness, conceptual understanding, and strengthen students' biology problem-solving skills (Lee & Lee, 2025; Nasir et al., 2024).

The application of the PjBL-STEM in biology learning, which is closely related to natural phenomena and real life, can provide an important foundation for designing project contexts. Through this approach, students not only learn abstract theoretical concepts through rote learning but also implement them in projects, thus training them to connect science with technology, perform simple engineering projects, and utilize mathematical skills. As a result, students can understand concepts more deeply while developing critical thinking, creativity, problem-solving and collaboration skills (Oanh & Dang, 2025). Previous research has demonstrated the effectiveness of the PjBL-STEM in improving learning quality. The implementation of PjBL-STEM can encourage students to connect various concepts learned, identify, and solve biology problems more efficiently, thereby increasing students' metacognitive awareness through real-life projects (Novitasari et al., 2024). PjBL-STEM is also more

effective in improving students' understanding of science concepts than conventional learning because students construct their own knowledge through real-life experiences (Yulaikah et al., 2022). Furthermore, PjBL-STEM encourages students to implement their knowledge in the form of project assignments. This facilitates students' understanding of material concepts related to real-life problems, positively impacting their problem-solving skills.

Previous studies examining PjBL-STEM have generally focused on only one or two variables, such as conceptual understanding or problem-solving, without examining their simultaneous relationship with metacognitive awareness. This indicates a gap in understanding the comprehensive impact of PjBL-STEM on biology learning. The uniqueness of this study lies in its integrated analysis of metacognitive awareness, conceptual understanding, and problem-solving skills simultaneously within a single PjBL-STEM framework. This integrated approach provides a more holistic perspective in preparing students for the challenges of 21st-century learning. Therefore, the simultaneous examination of this third variable is important because PjBL-STEM not only trains students to solve contextual problems through STEM integration but also encourages reflective processes during project completion. These reflective activities strengthen metacognitive awareness, which in turn supports deeper conceptual understanding and more structured problem-solving skills. Therefore, analyzing these variables simultaneously provides a more complete picture of the learning impact than examining them separately. The findings of this study are expected to contribute to enriching biology learning strategies that are more applicable and reflective, and able to improve students' metacognitive awareness, conceptual understanding, and problem-solving abilities. This study aims to analyze the effect of the Project-Based Learning learning model based on the STEM approach on metacognitive awareness, conceptual understanding, and biology problem-solving abilities students of class XI at SMA Negeri 13 Bone.

Method

Research Type

This research is a quasi-experimental. This type of research approximates a real experiment by testing the effect of one variable on another (Carter et al., 2024).

Research Time and Location

This research was conducted from January to April 2026, during the even semester of the 2025/2026

academic year. The research location was at SMA Negeri 13 Bone, Bone Regency, South Sulawesi Province.

Research Design

The research design used was a Pretest-Posttest Nonequivalent Control Group Design. This design involved two classes: an experimental class using a PjBL-STEM and a control class using the Direct Instruction (DI) model. The research design is presented in Table 1.

Table 1. Research Design

| Group | Pretest | Treatment | Posttest |
|------------|----------------|----------------------------|----------------|
| Experiment | O ₁ | X ₁ (PjBL-STEM) | O ₂ |
| Control | O ₃ | X ₀ (DI) | O ₄ |

Population and Sample

The population in this study consisted of six parallel classes of Grade XI A at SMA Negeri 13 Bone, with a total of 209 students. The sample was selected using a purposive sampling technique by choosing two classes with relatively similar academic abilities. Each class consisted of 36 students.

Research Procedure

The research procedures are presented in Figure 1.

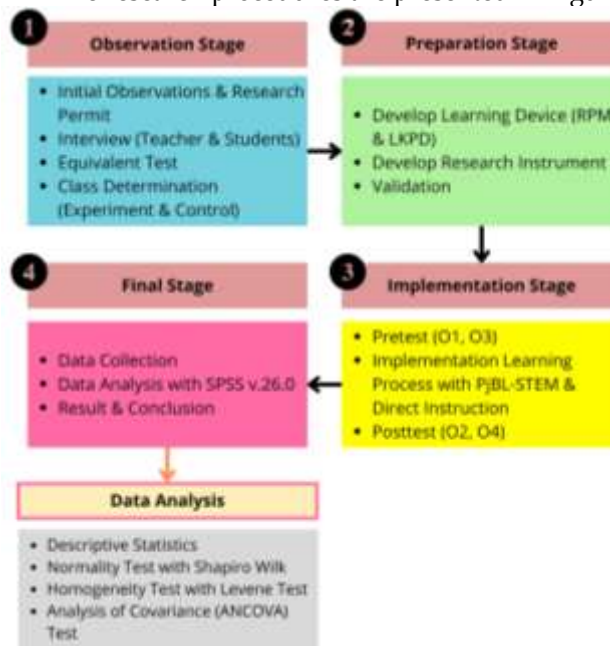


Figure 1. Research Procedure

Research Instruments

The research instrument consisted of the Metacognitive Awareness Inventory (MAI) questionnaire adapted from Schraw & Dennison, which consists of 40 items representing metacognitive knowledge and regulation. Conceptual understanding was assessed using 10 essay questions structured based on the SOLO (Structure of the Observed Learning

Outcomes) taxonomy, which classifies student responses into unistructural, multistructural, relational, and extended abstract levels. Prestructural responses were still accommodated in the analysis as indicators of misunderstanding or inappropriate responses to the given task. Biological problem-solving ability was measured using 8 essay questions representing Polya's (1973) problem-solving stages. In addition, a science process skills observation sheet was used as a supporting instrument to describe students' scientific activities during the implementation of PjBL-STEM and DI. These observations were conducted during six meetings in each class to interpreting students' learning. All instruments were validated by experts and tested for reliability prior to their use in the study.

Data Analysis Techniques

The data in this study were analyzed descriptively and inferentially. Descriptive statistical analysis was used to describe the lowest, highest, mean, and standard deviation scores. The following presents the intervals for the four variables measured in this study. The MAI questionnaire data, used to measure metacognitive awareness, uses the categorization ranges in Table 2.

Table 2. Categorization of Metacognitive Awareness

| Metacognitive Awareness Range | Category |
|-------------------------------|----------------------|
| 80 - 100 | Very Well Developed |
| 60 - 79.99 | Well Developed |
| 40 - 59.99 | Beginning to Develop |
| 20 - 39.99 | Not So Developed |
| 0 - 19.99 | Very At Risk |

Source: (Putera et al., 2021)

The concept understanding test sheet was arranged according to the SOLO Taxonomy understanding level and analyzed using the concept understanding categorization in Table 3.

Table 3. Categorization of Conceptual Understanding

| Conceptual Understanding Range | Category |
|--------------------------------|-----------|
| $80 \leq PK \leq 100$ | Very High |
| $60 \leq PK < 80$ | Tall |
| $40 \leq PK < 60$ | Enough |
| $20 \leq PK < 40$ | Low |
| $0 \leq PK < 20$ | Very Low |

Source: (Febriyana et al., 2021)

The biology problem-solving ability test sheet was analyzed descriptively using the categorization presented in Table 4.

Table 4. Categorization of Problem-Solving Skills

| Biology Problem-Solving Range | Category |
|-------------------------------|-----------|
| $85 \leq N \leq 100$ | Very Good |
| $70 \leq N < 85$ | Good |
| $55 \leq N < 70$ | Fair |
| $40 \leq N < 55$ | Poor |
| $0 \leq N < 40$ | Very Poor |

Source: (Pradiarti & Subanji, 2022)

Data from observations of students' science process skills during 6 meetings as supporting data were analyzed descriptively using the categorization in Table 5.

Table 5. Categorization of Science Process Skills

| Science Process Skills Range | Category |
|------------------------------|-----------|
| 86 - 100 | Very Good |
| 76 - 85 | Good |
| 60 - 75 | Fair |
| 55 - 59 | Poor |
| ≤ 54 | Very Poor |

Source: (Utami & Aryani, 2024)

Inferential statistical analysis was performed using SPSS version 26.0. Prior to hypothesis testing, prerequisite tests were conducted, including the Shapiro-Wilk test for normality and Levene's test for homogeneity of variance at a 5% significance level ($\alpha = 0.05$). Furthermore, separate ANCOVA (Analysis of Covariance) tests were conducted for each of the three dependent variables: metacognitive awareness, conceptual understanding, and biology problem-solving skills, with pretest scores as the covariate and posttest scores as the dependent variable.

Result and Discussion

The results of this study are presented using both descriptive and inferential analyses. Prior to reporting the main variables (metacognitive awareness, conceptual understanding, and problem-solving abilities), students' science process skills are first described as supporting data to provide contextual insight into the learning process. The descriptive statistics of students' science process skills are presented in Table 6. High scores in science process skills may indicate a positive alignment with the development of metacognitive, conceptual understanding, and problem-solving abilities awareness and other learning outcomes.

Table 6 shows that the average science process skills of students who were given the PjBL-STEM treatment obtained the lowest score at meeting I, namely 55.90 and the highest at meeting VI with an average of 92.24. Meanwhile, the average science process skills of students who were given the DI model treatment were

lowest at meeting I, namely 61.45 and the highest at meeting VI with an average of 87.38. When viewed from the average value of the students' KPS, it was found that the experimental class had a higher average compared

to the control class. The average science process skills of students based on indicators in classes taught with the PjBL-STEM and DI models are presented in Table 7.

Table 6. Distribution of Descriptive Statistics Values of Science Process Skills

| Class | Meeting | Number of Sample (N) | Lowest Score | Highest Score | Mean | Standard Deviation |
|-------------------------|---------|----------------------|--------------|---------------|-------|--------------------|
| PjBL-STEM | I | 36 | 41.67 | 75.00 | 55.90 | 7.54 |
| | II | 36 | 54.17 | 91.67 | 71.99 | 8.77 |
| | III | 36 | 66.67 | 95.83 | 79.51 | 6.63 |
| | IV | 36 | 62.50 | 95.83 | 82.87 | 6.88 |
| | V | 36 | 75.00 | 95.83 | 87.61 | 6.01 |
| | VI | 36 | 83.33 | 100.00 | 92.24 | 5.82 |
| Direct Instruction (DI) | I | 36 | 33.33 | 79.17 | 61.45 | 9.57 |
| | II | 36 | 45.83 | 83.33 | 65.39 | 8.78 |
| | III | 36 | 58.33 | 95.83 | 70.71 | 9.04 |
| | IV | 36 | 62.50 | 91.67 | 76.50 | 8.51 |
| | V | 36 | 66.67 | 95.83 | 82.06 | 8.72 |
| | VI | 36 | 75.00 | 100.00 | 87.38 | 7.80 |

Table 7. Distribution of Students' Science Process Skills based on Indicators in Experimental and Control Classes

| Science Process Skills Indicator | Experiment (PjBL-STEM) | | Control (DI) | |
|--|------------------------|----------|--------------|----------|
| | Mean | Category | Mean | Category |
| Observing | 81.83 | Good | 80.67 | Good |
| Questioning and predicting | 79.17 | Good | 76.39 | Good |
| Planning and conducting investigations | 79.86 | Good | 76.74 | Good |
| Processing, analyzing, and interpreting data | 82.06 | Good | 72.45 | Fair |
| Communicating results | 79.74 | Good | 70.60 | Fair |
| Evaluating and reflecting | 78.01 | Good | 66.67 | Fair |

The science process skills of students taught with the PjBL-STEM were all in the good category with the highest score being in the observing indicator, which was 81.83 and the lowest score being in the evaluating and reflecting indicator, which was 78.01. Meanwhile, the science process skills of students taught with the DI model obtained the highest score being in the observing indicator, which was 80.67 and the lowest score being in the evaluating and reflecting indicator, which was 66.67.

Metacognitive Awareness

The data from the descriptive statistical analysis of students' metacognitive awareness in classes taught using the PjBL-STEM and classes taught using the DI can be seen in Table 8.

Table 8. Distribution of Descriptive Statistics Values of Students' Metacognitive Awareness

| Descriptive Statistics | Experiment (PjBL-STEM) | | Control (DI) | |
|------------------------|------------------------|----------|--------------|----------|
| | Pretest | Posttest | Pretest | Posttest |
| Sample size | 36 | 36 | 36 | 36 |
| Lowest value | 38.50 | 58.00 | 37.50 | 53.50 |
| Highest value | 80.50 | 85.50 | 74.50 | 82.00 |
| Mean | 59.70 | 71.36 | 55.98 | 66.43 |
| Standard deviation | 8.94 | 5.39 | 9.67 | 7.07 |

Table 8 presents the average pretest score of metacognitive awareness of students who were given the PjBL-STEM treatment model of 59.70 ± 8.94 , with the lowest score of 38.50 and the highest score of 80.50. Meanwhile, the posttest data obtained a score of 71.36 ± 5.39 , with the lowest score of 58.00 and the highest score of 85.50. The average pretest score of metacognitive

awareness of students who were given the DI treatment model was 55.98 ± 9.67 , with the lowest score of 37.50 and the highest score of 74.50. Meanwhile, the posttest data obtained a score of 66.43 ± 7.07 , with the lowest score of 53.50 and the highest score of 82.00. The frequency distribution and percentage of the category of

students' metacognitive awareness scores can be seen in Table 9.

Table 9. Frequency Distribution and Percentage of Students' Metacognitive Awareness in the Experimental and Control Classes

| Value Interval | Category | Pretest PjBL-STEM | | Posttest PjBL-STEM | | Pretest DI | | Posttest DI | |
|----------------|----------------------|-------------------|-------|--------------------|-------|------------|-------|-------------|-------|
| | | F | % | F | % | F | % | F | % |
| 80 - 100 | Very well developed | 2 | 5.56 | 3 | 8.33 | 0 | 0 | 1 | 2.78 |
| 60 - 79.99 | Well developed | 12 | 33.33 | 31 | 86.11 | 10 | 27.78 | 28 | 77.78 |
| 40 - 59.99 | Beginning to Develop | 20 | 55.55 | 2 | 5.56 | 22 | 61.11 | 7 | 19.44 |
| 20 - 39.99 | Not so developed | 2 | 5.56 | 0 | 0 | 4 | 11.11 | 0 | 0 |
| 0 - 19.99 | Very at risk | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Table 9 shows that the average metacognitive awareness of students in the experimental class for the pretest was in the category of beginning to develop with a percentage of 55.55% (20 students) and the posttest was in the category of developing well with a percentage of 86.11% (31 students). Meanwhile, the average metacognitive awareness of students in the control class

for the pretest was in the category of beginning to develop with a percentage of 61.11% (22 students) and the posttest was in the category of developing well with a percentage of 77.78% (28 students). The frequency distribution graph of metacognitive awareness can be seen in Figure 2.

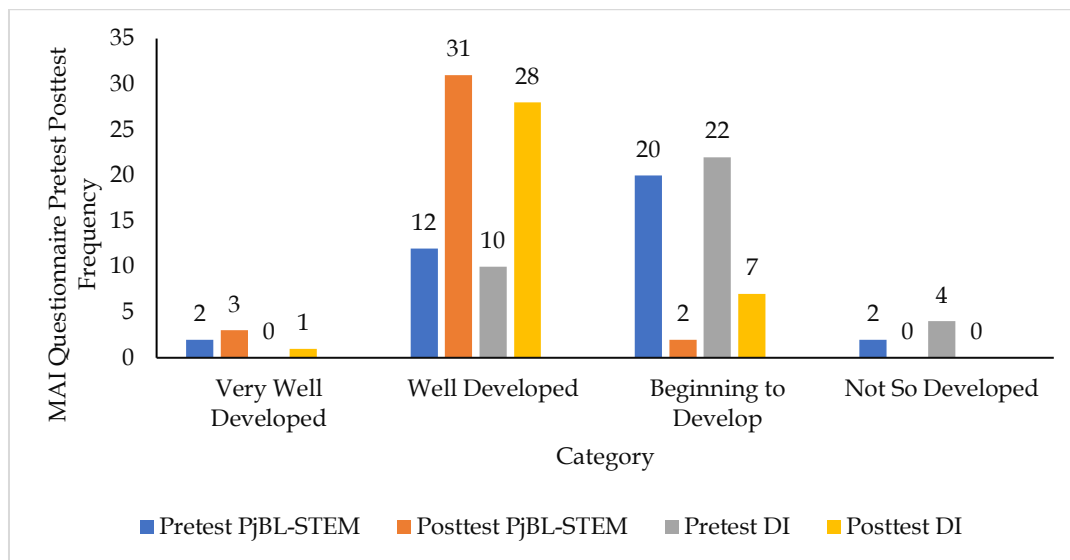


Figure 2. Frequency Distribution Graph of Students' Metacognitive Awareness

Based on the graph in Figure 2, before the implementation of the PjBL-STEM and DI models, most students in both classes had average metacognitive awareness scores in the "beginning to develop" category. After the implementation of the PjBL-STEM and DI models, most students in both classes improved to the "well develop" category. However, the percentage of students in the "well develop" category was higher in the experimental class, at 86.11% (31 students), compared to only 77.78% (28 students) in the control class.

The results of the metacognitive awareness normality test for students in experimental class XI A4 who received the PjBL-STEM treatment and control class XI A5 who received the DI treatment can be seen in Table 10.

Table 10. Metacognitive Awareness Normality Test Results

| Statistics | PjBL-STEM | | DI | |
|-------------|-----------|----------|---------|----------|
| | Pretest | Posttest | Pretest | Posttest |
| Sig. | 0.22 | 0.31 | 0.35 | 0.76 |
| Description | Normal | Normal | Normal | Normal |

Based on Table 10, the results of the metacognitive awareness normality test using the Shapiro-Wilk test obtained a significance value of 0.22 for the experimental class in the pretest and 0.31 for the posttest. Meanwhile, the significance value for the control class in the pretest was 0.35 and 0.76 for the posttest. The normality test data showed a Sig. (α) value > 0.05 , thus concluding that the metacognitive awareness scores of the experimental

class taught using the PjBL-STEM and the control class taught using the DI were normally distributed.

The homogeneity test data for the metacognitive awareness of students in experimental class XI A4 who received the PjBL-STEM treatment and control class XI A5 who received the DI treatment can be seen in Table 11.

Table 11. Results of the Metacognitive Awareness Homogeneity Test

| Statistics | Pretest | Posttest |
|-------------|---------|----------|
| Sig. | 0.53 | 0.06 |
| Description | Normal | Normal |

Based on Table 11, the results of the homogeneity test for metacognitive awareness using the Levene's Test obtained a significance value of 0.53 for the pretest and 0.063 for the posttest. The homogeneity test data showed a Sig. (α) value > 0.05 , thus concluding that the metacognitive awareness scores of the experimental class taught using the PjBL-STEM model and the control class taught using the DI model had homogeneous variance.

The data from the metacognitive awareness hypothesis test for students in experimental class XI A4 who were given the PjBL-STEM treatment and control class XI A5 who were given the DI treatment can be seen in Table 12.

Table 12. Results of the Metacognitive Awareness Hypothesis Test

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
|-----------------|-------------------------|----|-------------|--------|------|
| Corrected model | 1885.97 ^a | 2 | 942.98 | 49.27 | .000 |
| Intercept | 2930.08 | 1 | 2930.08 | 153.10 | .000 |
| Pretest | 1448.38 | 1 | 1448.38 | 75.68 | .000 |
| Learning model | 167.64 | 1 | 167.64 | 8.76 | .004 |
| Error | 1320.49 | 69 | 19.13 | | |
| Total | 344964.25 | 72 | | | |
| Corrected total | 3206.46 | 71 | | | |

Based on Table 12, the ANCOVA results showed that the learning model had a significant effect on students' metacognitive awareness ($F = 8.76, p = .004$). These results indicate that the PjBL-STEM has a significant effect on students' metacognitive awareness. Students' metacognitive awareness in this study was reviewed based on the results of data analysis, which showed changes after the learning process. Based on the descriptive analysis, it was found that both the experimental and control classes experienced an increase in their average metacognitive awareness scores. Although the difference in improvement between the two classes was relatively small, the experimental class still showed a higher increase than the control class. Furthermore, the shift in the frequency distribution showed that the percentage of students in the "well-developed" category in the experimental class reached 86.11% (31 students), higher than the control class at 77.78% (28 students). This indicates that PjBL-STEM is more effective in increasing students' metacognitive awareness than DI.

The comparison between the PjBL-STEM and DI in this study may seem contrasting. However, this design was intentionally used to demonstrate the effectiveness of a student-centered learning approach compared to common teaching practices in biology classrooms. Based on initial observations, teachers tended to use Direct Instruction. Therefore, this model was chosen as a control group to represent real-world learning

conditions, allowing this study to assess the added value of STEM integration in project-based learning.

The PjBL-STEM can encourage the development of students' metacognitive awareness more comprehensively, as reflected in each learning stage, which facilitates the planning, monitoring, and evaluation processes. This aligns with research by (Damayanti et al., 2026; O'Neill et al., 2025), which states that metacognition can encourage students to plan, monitor, and evaluate learning strategies, thus positively influencing their conceptual understanding. In the research and discovery stage, students are trained to plan and develop investigation strategies (planning). Next, in the application stage, students process, analyze, and monitor the alignment of results with the plan (monitoring). In the reflection and communication stage, students evaluate and reflect on the process and results obtained (evaluating). Student engagement in each PjBL-STEM learning syntax systematically encourages the development of metacognitive awareness.

The results of the science process skills measurement, as supporting data, indicate that students' scientific activities during the project were in the good category, particularly in the indicators of planning and conducting investigations, processing, and analyzing data, and evaluating and reflecting. High achievement in these indicators indicates that students not only carried out learning procedures but also engaged in a directed and controlled thinking process.

More specifically, the planning and conducting investigation indicator demonstrates students' ability to develop initial strategies (planning); the ability to process, analyze, and interpret data reflects monitoring of the thought process (monitoring); and the evaluating and reflecting indicator confirms students' ability to assess and improve their thinking processes (evaluating), which is the core of metacognitive awareness. Therefore, high levels of science process skills in these indicators not only demonstrate success in scientific skills but also demonstrate that students used metacognitive strategies during learning. This confirms that increased metacognitive awareness in the experimental class occurred through student engagement in the structured scientific process within PjBL-STEM.

These findings align with research by Fiteriani et al. (2021) which shows that the implementation of PjBL-STEM provides students with the opportunity to actively engage in the thinking process, thereby enhancing metacognitive abilities through planning, controlling, and reflecting on learning. Mulyani & Arif (2021) also emphasized that the implementation of the PjBL-STEM has been proven to significantly improve students' metacognitive abilities, as in the learning process, students are trained through the stages of problem analysis, hypothesis formulation, experiment

implementation, and conclusion drawing. Based on these findings, it can be concluded that the PjBL-STEM is not only statistically effective but also has practical implications for learning. This model can be used as an alternative learning model that can train students to think in a directed, independent, and reflective manner, although it requires more attention in the implementation of evaluations for optimal learning (Wati et al., 2024).

The concept of learning through experiments, investigations, and real-life projects encourages students to reflect on their learning experiences, thereby supporting the development of metacognitive awareness (Wu, 2024). Therefore, the implementation of PjBL-STEM not only contributes to developing students' metacognitive awareness but also fosters reflective thinking and independent learning, which are essential for 21st-century learning. Therefore, PjBL-STEM creates a learning process that focuses not only on activities but also on the continuous development of students' thinking skills.

Concept Understanding

The data from the descriptive statistical analysis of students' metacognitive awareness in classes taught using the PjBL-STEM and classes taught using the DI can be seen in Table 13.

Table 13. Distribution of Descriptive Statistics Values of Students' Concept Understanding

| Descriptive Statistics | Experiment (PjBL-STEM) | | Control (DI) | |
|------------------------|------------------------|----------|--------------|----------|
| | Pretest | Posttest | Pretest | Posttest |
| Sample size | 36 | 36 | 36 | 36 |
| Lowest value | 20.00 | 57.50 | 22.50 | 52.50 |
| Highest value | 70.00 | 97.50 | 62.50 | 92.50 |
| Mean | 46.11 | 81.67 | 42.15 | 75.07 |
| Standard deviation | 13.26 | 9.92 | 11.15 | 10.24 |

Table 13 presents the average pretest value of students' conceptual understanding given the PjBL-STEM treatment of 46.11 ± 13.26 , with the lowest value of 20 and the highest value of 70. Meanwhile, the posttest data obtained a value of 81.67 ± 9.92 , with the lowest value of 57.50 and the highest value of 97.50. The average pretest value of conceptual understanding given the DI treatment was 42.15 ± 11.15 , with the lowest value of 22.50 and the highest value of 62.50. Meanwhile, the posttest data obtained an average value of 75.07 ± 10.24 , with the lowest value of 52.50 and the highest value of 92.50. The frequency distribution and percentage of the category of students' conceptual understanding values can be seen in Table 14.

Table 14 shows that the average conceptual understanding of students in the experimental class for

the pretest was in the enough category with a percentage of 55.56% (20 students) and the posttest was in the very high category with a percentage of 61.11% (22 students). Meanwhile, the average conceptual understanding of students in the control class for the pretest was in the enough category with a percentage of 52.77% (19 students) and the posttest was in the high category with a percentage of 55.56% (20 students). The frequency distribution graph of conceptual understanding can be seen in Figure 3.

Table 14. Frequency Distribution and Percentage of Students' Concept Understanding in the Experimental and Control Classes

| Value Interval | Category | Pretest PjBL-STEM | | Posttest PjBL-STEM | | Pretest DI | | Posttest DI | |
|-----------------------|-----------|-------------------|-------|--------------------|-------|------------|-------|-------------|-------|
| | | F | % | F | % | F | % | F | % |
| $80 \leq PK \leq 100$ | Very high | 0 | 0 | 22 | 61.11 | 0 | 0 | 13 | 36.11 |
| $60 \leq PK < 80$ | Tall | 7 | 19.44 | 13 | 36.11 | 2 | 5.56 | 20 | 55.56 |
| $40 \leq PK < 60$ | Enough | 20 | 55.56 | 1 | 2.78 | 19 | 52.77 | 3 | 8.33 |
| $20 \leq PK < 40$ | Low | 9 | 25 | 0 | 0 | 15 | 41.67 | 0 | 0 |
| $0 \leq PK < 20$ | Very low | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

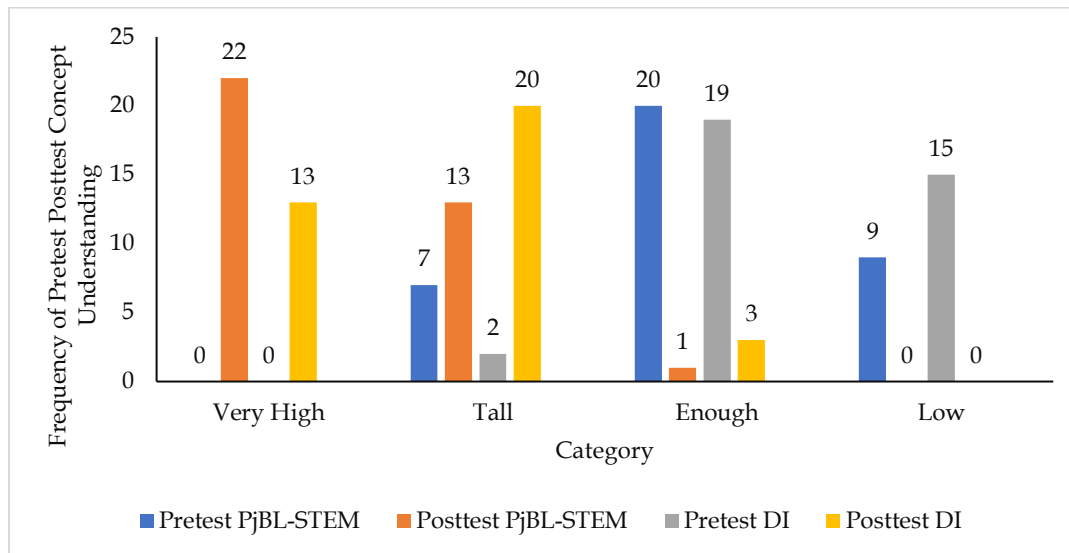


Figure 3. Frequency Distribution Graph of Students' Concept Understanding

Based on the graph in Figure 3, before the implementation of the PjBL-STEM and DI models, most students in both classes had average conceptual understanding scores in the enough category. After the implementation of the PjBL-STEM and DI models, there was an increase in both classes, with the experimental class improving to the very high category, while the control class improved to the high category.

The data from the normality test for conceptual understanding of students in experimental class XI A4, which received the PjBL-STEM treatment, and control class XI A5, which received the DI treatment, can be seen in Table 15.

Table 15. Results of the Concept Understanding Normality Test

| Statistics | PjBL-STEM | | DI | |
|-------------|-----------|----------|---------|----------|
| | Pretest | Posttest | Pretest | Posttest |
| Sig. | 0.57 | 0.27 | 0.28 | 0.41 |
| Description | Normal | Normal | Normal | Normal |

Based on Table 15, the results of the normality test for students' conceptual understanding using the Shapiro-Wilk test obtained a significance value of 0.57 for the experimental class in the pretest and 0.27 for the posttest. Meanwhile, the significance value for the

control class in the pretest was 0.28 and 0.41 for the posttest. The normality test data showed a Sig. (α) value > 0.05 , thus concluding that the conceptual understanding scores of the experimental class taught using the PjBL-STEM model and the control class taught using the DI model were normally distributed.

The homogeneity test results for students' conceptual understanding in experimental class XI A4, which received the PjBL-STEM treatment, and control class XI A5, which received the DI treatment, can be seen in Table 16.

Table 16. Results of the Concept Understanding Homogeneity Test

| Statistics | Pretest | Posttest |
|-------------|---------|----------|
| Sig. | 0.45 | 0.95 |
| Description | Normal | Normal |

Based on Table 16, the results of the homogeneity test for conceptual understanding using the Levene's Test obtained a significance value of 0.45 for the pretest and 0.95 for the posttest. The homogeneity test data showed a Sig. (α) value > 0.05 , thus concluding that the conceptual understanding scores of the experimental class taught using the PjBL-STEM and the control class taught using the DI had homogeneous variance.

The data from the hypothesis test for conceptual understanding of students in experimental class XI A4 who were given the PjBL-STEM treatment and control

class XI A5 who were given the DI treatment can be seen in Table 17.

Table 17. Concept Understanding Hypothesis Test Results

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
|-----------------|-------------------------|----|-------------|---------|------|
| Corrected model | 5027.549 ^a | 2 | 2513.774 | 60.342 | .000 |
| Intercept | 12708.596 | 1 | 12708.596 | 305.065 | .000 |
| Pretest | 4244.129 | 1 | 4244.129 | 101.879 | .000 |
| Learning model | 292.022 | 1 | 292.022 | 7.010 | .010 |
| Error | 2874.448 | 69 | 41.659 | | |
| Total | 450093.750 | 72 | | | |
| Corrected total | 7901.997 | 71 | | | |

Based on Table 17, the ANCOVA results showed that the learning model had a significant effect on students' conceptual understanding ($F = 7.01, p = .01$). These results indicate that the PjBL-STEM has a significant effect on students' conceptual understanding. Students' conceptual understanding after being exposed to the PjBL-STEM and DI learning models showed significant changes. Based on the descriptive analysis, both the experimental and control classes experienced an increase in their average conceptual understanding scores. In the experimental class, the average increased from 46.11 (pretest) to 81.67 (posttest), while in the control class, it increased from 42.15 (pretest) to 75.07 (posttest).

Before the model implementation, students' conceptual understanding in both classes was in the enough category. After implementing the model, the experimental class demonstrated optimal improvement, reaching the very high category with a percentage of 61.11% (22 students), while the control class only reached the high category with a percentage of 55.56% (20 students). Further review of the SOLO Taxonomy (Structure of the Observed Learning Outcomes) levels of thinking revealed that conceptual understanding in both the experimental and control classes had reached the "relational" level. However, the experimental class taught using the PjBL-STEM experienced a relatively higher improvement of 87.50 points compared to the control class, which only achieved 81.25 points. This finding indicates that students were able to integrate the various information obtained and understand the relationships between concepts comprehensively (Huang et al., 2024). The results showed that the PjBL-STEM model is capable of optimally encouraging the development of students' conceptual understanding. This improvement is inseparable from the integration of STEM elements into each stage of learning. In the reflection and research stage, students identify and analyze science-based biology problems, particularly those related to the excretory system and the coordination system, and utilize technology to access

supporting information and data. This process helps students build initial understanding from a unistructural to a multistructural level.

Next, in the discovery stage, students begin to design solutions using a technical approach by developing ideas and connecting various biological concepts, thus encouraging development to the relational level. In the application and communication stage, students test and apply solutions in real-world projects involving mathematical analysis, such as data processing and drawing conclusions. In the excretory system, students develop a simple model of the urine formation mechanism, while in the coordination system, students conduct sensory sensitivity tests. This activity encourages students to generalize knowledge and connect it to broader contexts, thus reaching an extended abstract level. Thus, the integration of science, technology, engineering, and mathematics elements in PjBL-STEM encourages active student engagement in the thinking process and contributes to improved conceptual understanding (Nurhayati et al., 2023). The student process in working on the project is presented in Figure 4.



Figure 4. Student project activities: (a) the process of working on a simple model project on the mechanism of urine formation; (b) testing sensory sensitivity in the coordination system.

The implementation of the PjBL-STEM not only improves students' conceptual understanding quantitatively but also qualitatively, moving from simple to more complex understanding. This is because PjBL-STEM learning is based on constructivism theory,

so students not only receive information but also actively construct and test their understanding through real-life projects (Naushabekov et al., 2025; Yulaikah et al., 2022). Furthermore, improved conceptual understanding is also supported by students' science process skills, which are in the good category, especially in the indicators of planning and conducting investigations, processing, and analyzing data, and evaluating and reflecting, indicating that conceptual understanding is formed through a structured and meaningful scientific process.

The findings of this study align with those of (Prajoko et al., 2023), who stated that PjBL-STEM can improve students' conceptual understanding because concepts and knowledge are built when students collaborate in groups to develop a project. This finding is also confirmed by Haryanti & Sarwi (2025), who stated that the PjBL-STEM has a positive impact on improving students' conceptual understanding because it allows them to systematically understand scientific processes. Through activities such as problem identification, research, discussion, experimentation, and reflection, students are trained to think critically, collaborate, and solve problems, thereby achieving a deeper understanding (Anwar et al., 2024). Furthermore, the implementation of STEM-based learning also encourages students to think more critically in analyzing and solving problems during the learning process (Haetami, 2023). As a result, the learning process is not only based on results but also on the scientific thinking process that serves as the foundation for developing understanding. The implication is that students are able to build a more contextual and applicable understanding while developing scientific understanding (Sujud et al., 2024).

PjBL-STEM encourages students to engage in meaningful learning activities, actively engaging them in the learning process. This approach can develop critical, creative, and analytical thinking (Zulyusri et al., 2023). Through this process, students' conceptual understanding can be formed because the learning process is realized through project activities. Thus, students not only gain understanding limited to the cognitive domain but also are able to relate it to life values (Kurniasari et al., 2023). This is further strengthened through the integration of PjBL-STEM, which combines various disciplines, making learning more active and meaningful. These conditions encourage students to engage in the process of exploration, investigation, and finding solutions to real-world problems, ultimately leading them to think more deeply and build a more complete conceptual understanding (Hendranti et al., 2025). In addition, the project-based learning model trains students to actively seek, discover, and express knowledge through direct involvement (Siyamuningsih et al., 2025). Thus, the implementation of PjBL-STEM is able to encourage the formation of a deeper and more meaningful understanding of students' concepts, because students not only acquire theoretical knowledge but are also able to relate it to real-world contexts through integrated project activities.

Biology Problem-Solving Skills

The data from the descriptive statistical analysis of the problem-solving abilities of students in the class taught using the PjBL-STEM and the class taught using the DI can be seen in Table 18.

Table 18. Distribution of Descriptive Statistics Values of Biology Problem-Solving Ability

| Descriptive Statistics | Experiment (PjBL-STEM) | | Control (DI) | |
|------------------------|------------------------|----------|--------------|----------|
| | Pretest | Posttest | Pretest | Posttest |
| Sample size | 36 | 36 | 36 | 36 |
| Lowest value | 34.38 | 65.63 | 28.13 | 62.50 |
| Highest value | 75.00 | 96.88 | 59.38 | 90.63 |
| Mean | 50.69 | 82.81 | 44.27 | 75.00 |
| Standard deviation | 11.05 | 7.70 | 9.25 | 6.51 |

Table 18 presents the average pretest score of biology problem-solving ability of students who were given the PjBL-STEM treatment of 50.69 ± 11.05 , with the lowest score of 34.38 and the highest score of 75. While in the posttest data obtained a score of 82.81 ± 7.70 , with the lowest score of 65.63 and the highest score of 96.88. The average pretest score of biology problem-solving ability given the DI treatment was 44.27 ± 9.25 , with the

lowest score of 28.13 and the highest score of 59.38. While in the posttest data obtained an average score of 75 ± 6.51 , with the lowest score of 62.50 and the highest score of 90.63. The frequency distribution and percentage of the category of students' biology problem-solving ability scores can be seen in Table 19.

Table 19. Frequency Distribution and Percentage of Students' Biology Problem-Solving Ability in Experimental and Control Classes

| Value Interval | Category | Pretest PjBL-STEM | | Posttest PjBL-STEM | | Pretest DI | | Posttest DI | |
|----------------------|-----------|-------------------|-------|--------------------|-------|------------|-------|-------------|-------|
| | | F | % | F | % | F | % | F | % |
| $85 \leq N \leq 100$ | Very good | 0 | 0 | 13 | 36.11 | 0 | 0 | 2 | 5.56 |
| $70 \leq N < 85$ | Good | 2 | 5.56 | 22 | 61.11 | 0 | 0 | 25 | 69.44 |
| $55 \leq N < 70$ | Fair | 12 | 33.33 | 1 | 2.78 | 7 | 19.44 | 9 | 25 |
| $40 \leq N < 55$ | Poor | 16 | 44.44 | 0 | 0 | 20 | 55.56 | 0 | 0 |
| $0 \leq N < 40$ | Very poor | 6 | 16.67 | 0 | 0 | 9 | 25 | 0 | 0 |

Table 19 shows that the average biology problem-solving ability of students in the experimental class for the pretest was in the poor category with a percentage of 44.44% (16 students) and the posttest was in the good and very good category, namely 61.11% and 36.11%. Meanwhile, the average biology problem-solving ability

of students in the control class for the pretest was in the poor category with a percentage of 55.56% (20 students) and the posttest was in the good and very good category, namely 69.44% and 5.56%. The frequency distribution graph of conceptual understanding can be seen in Figure 5.

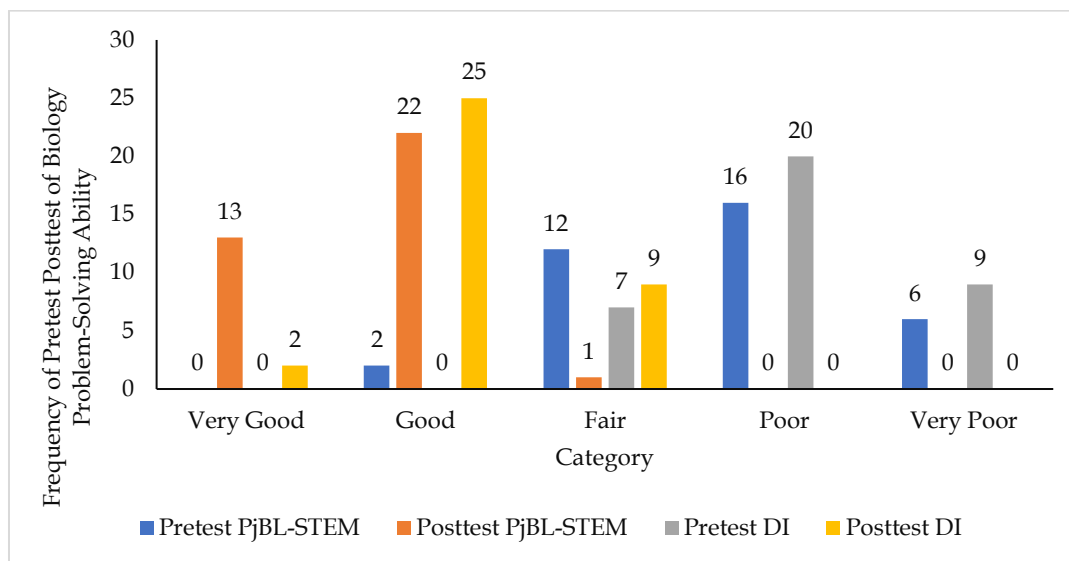


Figure 5. Frequency Distribution Graph of Students' Biology Problem-Solving Ability

Based on the graph in Figure 4, before the implementation of the PjBL-STEM and DI models, most students in both classes had average biology problem-solving ability scores in the poor category. After the implementation of the PjBL-STEM and DI models, the average biology problem-solving ability of students in both classes increased to the good category. Although the percentage of students in the good category in the control class was higher, at 69.44% (25 students) compared to the experimental class (61.11% (22 students), the results in the experimental class showed more optimal improvement.

Data from the normality test for the biology problem-solving ability of students in experimental class XI A4 who received the PjBL-STEM treatment and control class XI A5 who received the DI treatment can be seen in Table 20.

Table 20. Results of the Normality Test of Biology Problem-Solving Ability

| Statistics | PjBL-STEM | | DI | |
|-------------|-----------|----------|---------|----------|
| | Pretest | Posttest | Pretest | Posttest |
| Sig. | 0.06 | 0.37 | 0.06 | 0.20 |
| Description | Normal | Normal | Normal | Normal |

Based on Table 20, the results of the normality test of students' biology problem-solving abilities using the Shapiro-Wilk test obtained a significance value of 0.06 for the experimental class in the pretest and 0.37 for the posttest. Meanwhile, the significance value for the control class in the pretest was 0.06 and 0.20 for the posttest. The normality test data showed a Sig. (α) value > 0.05 , thus concluding that the biology problem-solving abilities of the experimental class taught using the PjBL-STEM model and the control class taught using the DI model were normally distributed.

The homogeneity test results for the biology problem-solving abilities of students in experimental

class XI A4 who received the PjBL-STEM and control class XI A5 who received the DI can be seen in Table 21.

Table 21. Results of Homogeneity Test of Biology Problem-Solving Ability

| Statistics | Pretest | Posttest |
|-------------|---------|----------|
| Sig. | 0.18 | 0.11 |
| Description | Normal | Normal |

Based on Table 21, the results of the homogeneity test of students' biology problem-solving abilities using

the Levene's Test obtained a significance value of 0.18 in the pretest and 0.11 in the posttest. The homogeneity test data showed a Sig. (α) value > 0.05 , thus concluding that the biology problem-solving abilities of the experimental class taught using the PjBL-STEM and the control class taught using the DI had homogeneous variance.

The data from the hypothesis test of the biology problem-solving abilities of students in experimental class XI A4 who were given the PjBL-STEM treatment and control class XI A5 who were given the DI treatment can be seen in Table 22.

Table 22. Biology Problem-Solving Ability Hypothesis Test Results

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
|-----------------|-------------------------|----|-------------|--------|------|
| Corrected model | 3021.23 ^a | 2 | 1510.62 | 63.48 | .000 |
| Intercept | 9176.55 | 1 | 9176.55 | 385.64 | .000 |
| Pretest | 1922.37 | 1 | 1922.37 | 80.78 | .000 |
| Learning model | 332.49 | 1 | 332.49 | 13.97 | .000 |
| Error | 1641.86 | 69 | 23.79 | | |
| Total | 452972.90 | 72 | | | |
| Corrected total | 4663.10 | 71 | | | |

Based on Table 22, the ANCOVA results showed that the learning model had a significant effect on students' biology problem-solving abilities ($F = 13.97, p < .001$). These results indicate that the PjBL-STEM has a significant effect on students' biology problem-solving abilities. The results of the descriptive and inferential analyses indicate that the PjBL-STEM has a significant effect on students' biology problem-solving abilities. Descriptively, the average score of students' biology problem-solving abilities in the experimental class increased from 50.69 (pretest) to 82.81 (posttest), and in the control class, it increased from 44.27 (pretest) to 75.00 (posttest). The improvement in students' biology problem-solving abilities was very good in the experimental class, with a total of 35 students (97.22%) ranking in the good and very good indicators, compared to only 27 students (75%) in the control class.

When examined further based on biology problem-solving ability indicators, the experimental class demonstrated more even and optimal development than the control class. In the experimental class, the most significant improvement was in the indicators of planning solutions and solving problems according to plan. This aligns with research by Subekti et al. (2025), which found that students appear more enthusiastic during the project design stage because they have more freedom to express their creative ideas. Meanwhile, the lowest scores were in the indicator of rechecking answers. This aligns with the findings of Rahayu et al. (2023), who found that students tend not to recheck their work and believe their work is correct and accurate, when it turns out to be incorrect.

Conversely, in the control class, although all indicators also improved to the good category, the progress tended to be uneven and relatively lower. The highest score was in the indicator of rechecking answers, while the indicator of solving problems according to plan still showed the lowest achievement. This indicates that students in the control class tended to perform better in the evaluation stage, but were not yet optimal in the stage of systematically implementing solutions.

This finding is reinforced by students' science process skills. In the experimental class, all KPS indicators consistently achieved good results, while in the control class, several indicators remained in the fair category. This indicates that the PjBL-STEM not only improves the outcome, namely problem-solving skills, but also optimizes students' scientific processes in obtaining, processing, and communicating information.

The results demonstrate that the PjBL-STEM is capable of developing students' problem-solving skills in biology. This success is due to the systematic implementation of the PjBL-STEM model syntax. In the reflection stage, students are trained to understand and identify problems, which is reflected in an increase in the problem understanding indicator. Next, in the research and discovery stage, students gather information and design solutions, resulting in the most significant increase in the solution planning indicator. In the application stage, students implement the solution according to the plan, resulting in an increased ability to solve problems systematically. In the communication stage, students present their results while simultaneously checking and reflecting on their answers, as reflected in the "re-checking" indicator. PjBL-

STEM learning can improve students' problem-solving skills because each stage of the project guides them to identify problems, process and analyze information, develop alternative solutions, and evaluate the project results (Anugrahsari et al., 2025; Dibyantini et al., 2023).

The PjBL-STEM model not only encourages the development of students' problem-solving skills but also helps them develop original ideas to systematically find solutions (Carlina et al., 2025). STEM-based learning encourages students to discuss, express ideas, and answer problems collaboratively according to learning stages (Putri *et al.*, 2023). This research finding aligns with the research of Purwaningsih et al. (2020), which found that the PjBL-STEM model is more effective in improving problem-solving skills than the discovery learning model. In discovery learning, the learning process tends to stop at the concept discovery stage without being followed by direct application in solving real-life problems. In contrast, in the PjBL-STEM, students not only understand concepts but also apply them through product design, testing, and evaluating the results. This process is crucial in biology learning, as the material is not limited to conceptual understanding but is also expected to provide meaningful experiences during the problem-solving process (Effendi & Yoto, 2024; Lestari et al., 2024).

The implementation of the PjBL-STEM encourages students to be more active in identifying problems and exploring their causes in depth. This aligns with the opinion of Diana et al. (2021) stated that PjBL-STEM is effective in helping students solve contextual problems through a systematic process. Along with this, students also become more skilled in determining appropriate problem-solving strategies, can apply conceptual knowledge in planning solutions, and conduct evaluations by comparing various available alternatives (Mahardhika & Hardianti, 2025). Thus, PjBL-STEM not only facilitates student engagement in understanding real-world problems but also helps link them to the learning process, particularly in developing problem-solving skills. Therefore, the application of this model is considered relevant in supporting the improvement of students' 21st-century competencies (Fauziah & Palennari, 2024).

Conclusion

In line with the research objective to analyze the effect of the project-based learning model based on the STEM approach, the results showed that the model significantly improved metacognitive awareness ($p=.004$), conceptual understanding ($p=.01$), and biology problem-solving abilities of students at SMA Negeri 13 Bone ($p<.001$). These findings confirm that the PjBL-

STEM is effective in improving these three aspects, while simultaneously forming a more directed, systematic, and reflective thinking process through active engagement at every stage of learning. Theoretically, these results strengthen and expand the literature on the effectiveness of PjBL-STEM in biology learning, particularly in integrating metacognitive development, conceptual understanding, and problem-solving abilities simultaneously. However, these findings are still limited to one educational institution and specific biology material. Therefore, further research is recommended to use a more robust experimental design, involve a wider sample, test the sustainability of learning effects in the long term, and integrate other variables to enrich the findings.

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Author Contributions

Conceptualization, methodology, formal analysis, investigation, resources, data curation, writing-original draft preparation, visualization, project administration, N.F.; validation, writing-review, and editing, N.F., F.D., Y.H., M.P., and N.B.; supervision, F.D. and Y.H. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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