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Critical Thinking Skills of College Students in Solving Linear Algebra Problems Using the Problem-Based Learning Model

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ABSTRACT

Third-semester electrical engineering students taking linear algebra had an average pretest of 54.2, indicating poor conceptual mastery of critical thinking skills (CTS). They struggled with variable analysis, mathematical inferences, and logical engineering problem solutions. This report suggests an innovative learning model that bridges mathematical theory and engineering applications. This study examines whether Problem-Based Learning (PBL) improves students' CTS and explains the qualitative mechanisms. This study employs an explanatory sequential mixed-methods approach. To measure CTS pre- and post-test scores using Facione indicators (interpretation, analysis, evaluation, inference, and explanation), 42 electrical engineering students were tested. In the second stage (quantitative), the researchers explained the quantitative results through observation of the learning process, in-depth interviews, and document analysis. The findings indicate the CTS score increased 31.2% from 54.2 to 71.1. The paired t-test (T (41) = 8.72; p < 0.001) confirmed statistical significance, while the Cohen's d Effect Size value of 1.39 indicated significant practical impact. 10 The Inference (44%) and Analysis (38%) indicators increased most. The qualitative results indicated that PBL forced students to think investigatively instead of procedurally. High group activity also improved students' explanation and evaluation skills (p = 0.006) by encouraging coherent arguments. With PBL, electrical engineering students' CTS, especially higher order thinking skills like analysis and inference, improved greatly. Positive group dynamics and changes in students' learning experiences, which PBL promotes to develop critical thinking and engineering-relevant problem-solving skills, supported this effectiveness.

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1. INTRODUCTION

Engineering education has been affected by Industry 4.0 and Society 5.0 (Broo et al., 2022; Puspitarini, 2022). Critical thinking, creativity, communication, and collaboration are essential for engineering students (Adhelacahya, 2023). Graduates learn four 4C skills to adapt to rapid technological change. Electrical engineers' mathematical analysis, system modeling, simulation, hardware and software development, and comprehensive engineering problem solving complicate these requirements (Purnomo et al., 2023). When solving linear algebra problems, electrical engineering students must think critically (Anggaini, 2020; Dwi Anggaini et al., 2020; Kim & Lee, 2022). Control systems, robotics, digital signal processing, electrical networks, machine learning algorithms, and numerical computation use linear algebra (Bayro-Corrochano, 2021; Sutrisno, 2023).

Previous research shows engineering students struggle with linear algebra (Conde-Carmona et al., 2024; Li & Chen, 2024). Vector spaces, linear transformations, eigenvalues, eigenvectors, determinants, and matrices in electrical systems are abstract and require higher-order thinking (Septiani et al., 2017). Students can mechanically perform matrix operations, but transformations and linear relationships are hard. Traditional lecture-based learning hurts them. Lecturers teach formulas and problem-solving (Busahdiar et al., 2023). Students rarely actively explore, analyze, and construct understanding with this model. Thus, many students memorize procedures without understanding concepts. This condition impairs students' critical thinking, especially when solving new math problems.

Problem-based learning and other constructivist pedagogies have been used to address this issue (Muzaini et al., 2022). PBL encourages students to think, discuss, investigate, and solve real problems (Anggraeni et al., 2023; Hasbi & Fitri, 2023). PBL is relevant because electrical network analysis, circuit systems of linear equations, transformation algorithms, and dynamic system modeling use linear algebra. The PBL linear algebra learning model improves electrical engineering students' critical thinking, according to Adhelacahya et al. (2023). The study uses Facione's indicators and statistical analysis to assess critical thinking (Jaelani et al., 2023). This study analyzes student learning interpretation using open coding and thematic analysis. This mixed-methods study examines PBL's effects on critical thinking and student learning (Hussin et al., 2025).

21st-century education emphasizes critical thinking (Thornhill-Miller et al., 2023; Wijngaards-de Meij & Merx, 2018). All graduates, especially engineering students, must think critically in an age of rapid technological advancement and complex problem-solving (Fatayan et al., 2024). Critical thinking allows people to objectively evaluate information, recognize logical patterns and relationships, evaluate alternative solutions, and make decisions based on sound reasoning and valid evidence. Critical thinking involves systematic cognitive abilities, interpretation, analysis, evaluation, inference, explanation, and self-regulation (Akcaoğlu et al., 2023; Altun & Yildirim, 2023). These six indicators can be measured in student learning activities, especially in linear algebra courses that require high mathematical reasoning.

Interpretation involves classifying and meaning information (Adhelacahya, 2023). Students must interpret electrical circuit coefficient matrices, variable relationship graphs, and linear algebra data (Benedicto & Andrade, 2022). Strong interpretation skills allow engineering students to understand mathematical symbols, connect visuals to mathematical models, and re-explain linear relationships (Cahyono, 2017). An electrical circuit diagram with nodes and resistors must be converted into Kirchhoff's law linear equations by students. The second indicator is analysis—identifying problem components, understanding variable relationships, and simplifying complex problems into logical components (Siregar & Sari, 2020). Linear algebra requires analysis because engineering math problems involve interacting variables (Kalnins, 2024). When faced with a system of linear equations describing electrical circuit current distribution, students must identify the main variables, system parameters, and how changing one variable affects the entire system.

Information validity, solution logic, and arguments or evidence is evaluated (Arikunto, 2018). Students in linear algebra evaluate whether Gaussian elimination is faster than matrix inverse, determinants are calculated correctly, and a system of equations is solved correctly. Assess computational precision and argumentation (Wirawan, 2016). Poor evaluators ignore errors and assumptions, resulting in invalid calculations. Fourth, inference involves drawing conclusions from data. Using eigenvalues and eigenvectors, linear algebra students infer system stability or predict conditions (Xin, 2019). Students must comprehend math and draw conclusions from evidence.

Structured explanations illustrate methods, strategies, and solutions. Linear algebra students learn this by solving linear equations or justifying methods (Umam et al., 2024). A clear, logical, and evidence-based explanation requires conceptual and communication skills. Self-regulation lets one assess thoughts. Self-regulated students can spot calculation errors, rethink solution logic, and try new methods when they fail (Chen & Hwang, 2019). Students must evaluate linear algebra solution steps, assumptions, and mathematical models to ensure they accurately represent engineering phenomena.

These six critical thinking indicators cover linear algebra cognitive skills (Qurohman et al., 2025). Students must interpret data, analyze mathematical structures, evaluate solution steps, draw logical inferences, explain problem-solving strategies, and critically reflect on their learning to understand linear algebra (Pahmi, 2020). Because engineering mathematics requires a profound understanding of concepts, the ability to apply theory to real-world situations, and the ability to solve complex problems systematically and logically, linear algebra requires critical thinking (Sari et al., 2025). Critical thinking is needed for electrical engineering students to face technological challenges.

PBL is a novel learning method that uses real problems. Instead of theory, examples, and practice, PBL starts with a professional issue (Adhelacahya, 2023). In constructivist theory, active thinking, exploration, social interaction, and hands-on learning build knowledge. Medical, engineering, science, and other complex problem-solving fields use PBL (Condliffe et al., 2017). PBL helps engineering math students understand concepts rather than memorize linear algebra procedures.

Teaching begins with real-world problems. Circuit analysis, node current calculations, dynamic system modeling, signal transformation, and matrix programming are electrical engineering problems (Kadek & Nugraha, 2019). Students should be challenged by complex problems that can be solved with linear algebra concepts. Authentic problems inspire students to research, analyze, and learn math, say Suyedi and Idrus (2019). Student groups identify known and unknown variables and mathematical relationships after receiving a problem. This stage is crucial for helping students map the problem structure and find key information. Students must use Kirchhoff's laws to identify circuit nodes, components, resistance, current direction, and equations.

Conceptual knowledge is needed for all PBL problems. Review matrix operations, Gaussian elimination, determinants, linear transformations, and eigenvalues. Concepts are explored through reading modules, independent research, and lecturer explanations. Small-group CBL students work. Group members discuss opinions, solutions, evaluations, and mathematical approaches (Cho & Brown, 2013). Group discussions practice mathematical communication, collaboration, argumentation, and academic leadership. The student brainstorms solutions after discussion. Before choosing, they compare elimination, matrix inverse, LU decomposition, and numerical methods. Students assess each method's computational efficiency, error rate, and system structure. Each group displays its solution to the class. This presentation helps students present mathematical arguments logically (Prasojo & Yuliana, 2021). After criticism, presentations encourage students to defend their claims. The reflection stage includes individual and group process evaluations. Student learning, challenges, collaboration, and how PBL improves linear algebra understanding are discussed (Ayyıldız Altınbaş et al., 2025). PBL helps linear algebra students learn after rote. Students follow the lecturer's procedures but understand why and how they represent engineering phenomena (Devika et al., 2024).

Most electrical engineering fields need linear algebra (Li & Chen, 2024; Semenova et al., 2022). Engineers can model many systems as linear systems for analysis, design, and simulation. Understanding complex engineering systems requires matrices, vectors, vector spaces, linear transformations, determinants, eigenvalues, and decompositions. Kirchhoff linear equations simulate electronic circuits (Semenova et al., 2022). A matrix representation of electrical network currents and voltages and linear equation solutions show node current distribution. Linear algebra covers conductance and admittance matrices.

Linear regression and system parameter estimation use least squares. Because of its broad scope, electrical engineering students must understand linear algebra conceptually and practically. Engineering students require a solid understanding of linear algebra and mathematics (Semenova et al., 2022). Critical thinking is needed to interpret calculation results, analyze variable relationships, evaluate mathematical solutions, and draw linear model inferences (Varveris et al., 2022).

Advanced course performance can suffer from linear algebra deficiencies. Control systems, circuit analysis, and signal engineering, control systems, control systems, control systems, control systems, and signal engineering challenge linear algebra students. Innovative learning methods like problem-based learning (PBL) help students learn concepts by solving real-world problems. Therefore, this study examines whether Problem-Based Learning (PBL) improves students' CTS and explains the qualitative mechanisms

2. METHOD

This research employed a mixed-methods explanatory approach. The first stage was quantitative data collection in the form of pre- and post-tests on critical thinking skills. The second stage was data in-depth analysis through observation of the learning process, interviews, and document analysis. The research subjects were 42 third-semester Electrical Engineering students studying Linear Algebra.

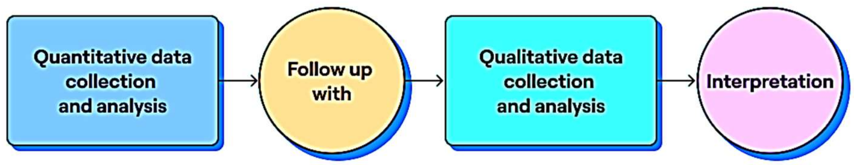

Figure 1. Mixed-Methods Explanatory Approach

Research instruments play a crucial role in generating accurate, reliable, and relevant data for the research objectives (Wirawan, 2016). In this study, which examined the application of Problem-Based Learning (PBL) in Linear Algebra to develop students' critical thinking skills, various instruments were systematically developed to capture the learning process, changes in cognitive abilities, group interaction dynamics, and students' learning experiences in greater depth. The instruments used included a critical thinking skills test, PBL observation sheets, in-depth interview guidelines, and document analysis of group work results.

Quantitative data analysis was conducted in several steps: (1) Descriptive Statistics: Calculating the mean score, standard deviation, and percentage increase (gain) from pretest to posttest (Anggaini, 2016). (2) Paired Samples T-Test: Used to test the significance of the difference between the overall mean pretest and posttest CTS scores. The third step involves calculating Cohen's d to ascertain the practical significance of the intervention. (4) One-Way ANOVA: Used to compare the mean increase (gain scores or adjusted posttest scores) among the five different CTS indicators (Interpretation, Analysis, Evaluation, Inference, and Explanation). The goal was to confirm and statistically quantify which indicator had the most significant improvement (Anggaini et al., 2018).

Qualitative data were analyzed using thematic analysis: (1) Coding: Data from interview transcripts and observations were coded to identify central categories. (2) Theme Development: Key themes are developed (e.g., “Investigative Thinking,” “Increased Coherence of Group Arguments,” “Changes in Learning Patterns”). (3) Data Integration: Qualitative findings are integrated with quantitative results to provide contextual explanations. For example, qualitative findings about high group activity are used to point out significant improvements in explanation and evaluation skills.

3. RESULTS AND DISCUSSION

Results

Descriptive Analysis of Critical Thinking Skill Improvement

Students' critical thinking skills (CBT) were measured before and after the PBL intervention using an instrument based on Facione indicators (Interpretation, Analysis, Evaluation, Inference, and Explanation).

Overall, there was a significant increase in CBT scores. The pre-test average was 54.2, indicating that students' CBT scores were in the adequate category but had not yet reached ideal conceptual mastery. After the PBL implementation, the post-test average increased to 71.1, representing an increase of 16.9 points or 31.2% from the initial score. This improvement indicates that students experienced substantial progress in their understanding of Linear Algebra concepts, their skills in working with mathematical data, and their ability to assess solution strategies.

Qualitative Explanation of Improvements Based on Indicators

The following table shows the improvement in scores each critical thinking skills indicator after PBL implementation:

Table 1. Critical Thinking Skills Score

Indicators	Pre-test	Post-test	Percentage
Interpretation	56	68	21%
Analysis	52	72	38%
Inference	50	72	44%
Evaluation	55	69	25%
Explanation	58	73	26%

The highest improvements occurred in the Inference (44%) and Analysis (38%) indicators.

Inference and Analysis (Highest Improvements: 44% and 38%)

The highest improvements in Analysis and Inference were reinforced by the results of observation and document analysis.

- Analysis (38%): At the beginning of the study, students tended to follow procedural steps without a logical basis. This improvement was explained by observations, where PBL trained students to break down problems into smaller parts, analyze relationships between variables, and evaluate relevant mathematical assumptions. This improvement was also reflected in document analysis, which showed improvements in their ability to construct mathematical models of engineering phenomena.
- Inference (44%): This improvement indicates that students successfully developed the ability to draw conclusions based on mathematical evidence. PBL provides space for students to compare alternative solutions, generate hypotheses, and draw inferences from solution exploration. This was clear in how students predicted

system behavior based on eigenvalues or solutions to Systems of Linear Equations (SPL).

Interpretation (21% Improvement)

The improvement in interpretation skills is supported by observations that students became more skilled at reading and understanding coefficient matrices, SPL structures, and graphs of variable relationships in engineering problems. Previously, they had difficulty understanding the mathematical meaning of matrix representations. After PBL, they were better able to interpret systems as linear combinations or relationships between variables. Observations confirmed that students had a better understanding of the technical meaning of matrix representations.

Evaluation and Explanation (25% and 26% Improvement)

PBL also had a positive impact on evaluation and explanation skills:

- Evaluation (25%): Students became better able to assess the strengths and weaknesses of solution methods, such as comparing Gaussian elimination with matrix inverses. At the end of the course, students were more critical of calculation results and validated their answers more frequently, indicating increased self-correction.
- Explanation (26%): Students' mathematical communication skills improved. PBL encouraged presentations and discussions. Interview results (as a qualitative follow-up) will demonstrate how group discussions accustomed them to expressing ideas systematically, a key component of this improvement.

Inferential Analysis and PBL Effectiveness

Inferential analysis confirmed that the increase in the PBL score was a direct result of the PBL intervention, not due to chance.

- Paired Sample T-Test: The difference between the pre-test and post-test was statistically significant ($T(41) = 8.72$; $p < 0.001$). This finding strengthens the conclusion that PBL is effective in improving PBL in Electrical Engineering students. The PBL process, which begins with real-world problems, encourages in-depth thinking, analysis, mathematical investigation, and the development of more appropriate solution strategies.
- Effect Size: Cohen's d value of 1.39 is categorized as a large effect (approaching very large). This indicates that PBL has a strong and practically significant impact on improving students' PBL.

Effect of Group Activity (ANOVA) and Qualitative Explanation

A one-way ANOVA analysis was conducted to determine whether the level of group activity (high, medium, low) affected score improvement.

- ANOVA Results: There was a significant effect of group activity on the improvement of the CBC ($F(2,39) = 5.82$; $p = 0.006$).
- Qualitative Explanation (Observation): This result is explained by field observations, which showed that students with high levels of activity experienced

greater score improvements. Observations also confirmed that PBL encourages collaborative work, where groups work more cohesively, tasks are better distributed, and students support each other. This suggests that positive group dynamics are a key mechanism in PBL mediating the improvement of the CBC, as active participation in discussions, data analysis, and opinion expression provides the greatest benefits.

Interview Results (In-Depth Learning Experience)

In-depth interviews were conducted with selected subjects (especially those who demonstrated significant score increases) to explore their learning experiences and gain a direct understanding of the processes that led to improvements in critical thinking skills (CBT). The interview results served as qualitative explanations that validated the quantitative findings and observations.

Encouragement to "Think Deeper" (Explanation of Improved Analysis and Inference)

Students reported that the real-world problem context in PBL forced them to shift from passive learning (following procedures) to active thinking (investigation).

"Previously, in regular lectures, I just followed the lecturer's procedures, making sure the answer was correct. In PBL, we had to 'break down' the circuit problem itself, analyzing which were the main variables and which ones needed matrix modeling. This realization helped me better understand why I needed to use the method, not just how to do it." (Student 2)

This recognition is relevant to explaining the highest increases in the Analysis (38%) and Inference (44%) indicators. PBL transformed students' initial weaknesses (only procedural) into strengths (analysis of variable relationships and drawing logical conclusions).

The Role of Group Discussion in Explanation

Students felt that the presentation and group discussion activities, which are characteristic of PBL, were crucial in strengthening their mathematical communication skills (Explanation).

"Group discussions force me to explain my ideas to my peers. If our ideas are wrong or illogical, the other group members immediately correct them. Therefore, when I take the post-test or work on new problems, I'm used to constructing neat and coherent mathematical arguments, not just random ones." (Student 11)

This interview finding directly explains the 26% increase in the Explanation indicator and supports the ANOVA results, which indicate that the level of group activity influences score improvement. Students who actively speak up and explain their ideas benefit the most.

Increased Self-Confidence and Critical Thinking (Evaluation)

The PBL process also fosters ownership and critical thinking (evaluation) of the solutions they identify, as they must justify their choice of methods and results.

"I've become more confident in evaluating solutions. Previously, we only received information from the lecturer, but now we must compare it ourselves, for example, why Gaussian elimination is more efficient than matrix inverse for this problem. This sense of 'ownership' of the solution makes me more critical of the result and encourages me to always validate my answer. (Student 18)

This result reinforces the quantitative findings regarding a 25% increase in the evaluation indicator, indicating that PBL successfully instills self-correction and critical evaluation of solutions in students.

In summary, the interview results explicitly explain that the improvement in PBL not only occurs at the score level (quantitative) but is also accompanied by positive changes in students' learning experiences, attitudes, and problem-solving strategies. PBL provides the context, structure, and motivation needed for electrical engineering students to apply their PBL to engineering problems.

Discussion

This discussion interprets and integrates quantitative and qualitative findings in depth, in accordance with a mixed-methods explanatory sequential design framework, to explain the mechanisms behind the effectiveness of Problem-Based Learning (PBL) in improving Electrical Engineering students' Critical Thinking Skills (CTS).

PBL Effectiveness and Statistical Significance

The quantitative research results show that the implementation of the PBL model significantly increased the average CTS score of students, from 54.2 (pre-test) to 71.1 (post-test). This 31.2% increase was confirmed by inferential analysis. A paired sample t-test showed that this difference was statistically significant ($T(41) = 8.72$; $p < 0.001$), confirming that the CTS increase was truly a result of the PBL intervention and not a random factor.

Furthermore, the Cohen's d Effect Size calculation yielded a value of 1.394. This value is categorized as a large effect, even approaching the very large category. This indicates that PBL is not only statistically significant but also practically significant.6 This means that PBL has a strong impact on almost all research subjects, making it a highly effective model for learning Linear Algebra for engineering students (Adhelacahya et al., 2023; Semenova et al., 2022).

Qualitative Explanation of the Mechanism of Improvement in CTS

The explanatory research design requires qualitative data to explain how and why the quantitative score increases occurred. Qualitative findings (observations and interviews) provide an in-depth explanation of the highest increases, namely the Inference (44%) and Analysis (38%) indicators.

Improvement in Analysis and Inference

The substantial improvement in Analysis and Inference is explained by changes in student mindsets recorded in the interviews: (1) Students acknowledged that the real-world problem context in PBL forced them to shift from passive learning ("following procedures") to active thinking ("investigating"). (2) Observations indicate that PBL trains students to break down problems into smaller parts, analyze relationships between variables, and evaluate relevant mathematical assumptions. This improvement was reflected in document analysis, where students' ability to construct mathematical models of engineering phenomena improved. (3) Improved inference occurred because PBL provided a space for comparing alternative solutions and drawing conclusions based on mathematical evidence. This shift from purely procedural to investigative, as acknowledged by Student 2 ("understanding why to use that method, not just knowing how"), is key to PBL's success in improving Analysis and Inference skills.

The Role of Group Cohesiveness in Explanation

Improvements in the Explanation (26%) and Evaluation (25%) indicators were strongly related to PBL group dynamics: (1) ANOVA results ($p = 0.006$) indicate that the level of group activity significantly influenced score improvement. Observations confirmed that students with high activity experienced greater score improvements, as PBL encourages collaborative work, cohesiveness, and good task distribution. (2) Interviews provided direct evidence that group discussions and presentations force students to construct coherent and coherent mathematical arguments. Direct peer correction during discussions is an important mechanism that strengthens their mathematical communication skills, explaining why students who are active in discussions (high activity groups) benefit the most. (3) The need to defend solutions to other groups also fosters a sense of "ownership" of the solution. This makes students more critical of calculation results and accustomed to validating answers, which is the essence of the Evaluation indicator.

Integrative Conclusions (PBL as a Catalyst)

Overall, the results of this study confirm that PBL is effective because it transforms students' learning experiences (Devika et al., 2024; Hsbollah & Hassan, 2022; Prosser & Sze, 2014). Rather than simply improving scores (quantitative data), PBL acts as a catalyst that motivates in-depth thinking through contextual engineering problems, provides a structure for breaking down, analyzing, and modeling problems (Analysis/Inference), and requires communication and justification of ideas (Explanation/Evaluation) through group dynamics. By combining strong quantitative evidence (significance and effect size) with in-depth qualitative evidence (observations and interviews), this study successfully demonstrates not only that PBL is effective but also provides a rich understanding of how PBL works in a Linear Algebra class for Electrical Engineering students.

This study provides a profound scientific contribution by not only proving that PBL is effective but also explaining how PBL mechanisms work to improve critical thinking skills through the integration of qualitative data. Interview findings explicitly demonstrate students' shift from passive/procedural thinking to active/analytical and investigative thinking, which directly explains the significant improvement in scores (especially Analysis 38% and Inference 44%). This study recommends PBL as a highly effective model for Linear Algebra courses, especially for Electrical Engineering students. This contribution is relevant for engineering study programs that require in-depth mathematical applications to engineering problems (such as circuits). Furthermore, these results emphasize that PBL not only improves cognitive skills (Critical Thinking Skills) but also promotes essential engineering skills, such as problem modeling and teamwork (group cohesiveness). This helps engineering educators in designing curricula that integrate soft skills and hard skills simultaneously.

4. CONCLUSION

The implementation of PBL significantly improved electrical engineering students' critical thinking skills (CTS). The average CBT score increased from 54.2 (pre-test) to 71.1 (post-test). Inferential analysis showed this difference in scores was statistically significant ($p < 0.001$). PBL demonstrated a strong practical impact on CTS improvement, as indicated by a Cohen's d Effect Size value of 1.39. This confirms that PBL is a highly effective learning model for courses requiring in-depth mathematical reasoning. The highest score increases occurred in the Inference (44%) and Analysis (38%) indicators. This increase was qualitatively explained by the fact that PBL forces students to shift from procedural thinking to analytical and investigative thinking. Furthermore, high activity and participation in PBL groups significantly influenced CBT improvement ($p = 0.006$). Interview results confirmed that group discussions and presentations play a crucial role in training students to construct coherent arguments (explanation) and critically assess solutions (evaluation).

As a suggestion, lecturers in engineering study programs, especially in courses that require high-level mathematical modeling such as linear algebra, are strongly advised to adopt the PBL model. The implementation of PBL should focus on providing authentic engineering problems that can trigger students' analysis and inference skills. Lecturers need to explicitly monitor and facilitate group dynamics to ensure equitable and optimal participation. Because group activities have a significant influence, assessment strategies should include student contributions and communication within the group to maximize cognitive benefits. Although PBL is effective, future researchers are advised to focus on developing specific instruments or interventions to further strengthen the Interpretation indicator (21%), which has the lowest percentage of improvement compared to Inference and Analysis. Furthermore, future research can use similar mixed-methods designs to test the effectiveness of PBL on other variables, such as problem-solving skills or mathematical modeling abilities, to enrich the engineering pedagogy literature.

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