

Implementation of Problem-Based Learning Model to Improve Mathematical Problem-Solving Skills of Grade XI-2 Students of SMAN 19 Pekanbaru

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Article Info

Article History

Submitted: 18-01-2026

Revised: 20-04-2026

Accepted: 21-04-2026

Keywords:

Problem-Based Learning;
Mathematical problem-solving ability;
Classroom action research;
Reflective reasoning;
Higher-order thinking skills

Abstract

This study aimed to improve students' mathematical problem-solving ability through the implementation of the Problem-Based Learning (PBL) model in mathematics instruction. The study employed a collaborative Classroom Action Research (CAR) design conducted in two cycles involving planning, implementation, observation, and reflection stages. The participants consisted of 41 students of Grade XI-2 at SMAN 19 Pekanbaru during the odd semester of the 2025/2026 academic year. Data were collected through classroom observation and mathematical problem-solving ability tests based on four indicators adapted from Polya's problem-solving framework, namely understanding the problem, planning the solution, carrying out the solution, and checking back. Data analysis was conducted quantitatively and qualitatively to examine the progression of students' mathematical problem-solving performance and classroom learning activities across cycles. The findings revealed that the implementation of PBL contributed positively to improving both the learning process and students' mathematical problem-solving ability. The average class score increased from 33.90 in the initial test to 67.80 in Cycle I and further improved to 73.41 in Cycle II. Improvement was also observed across all problem-solving indicators, particularly in the planning and checking back indicators, indicating stronger strategic reasoning and reflective evaluation skills among students. In addition, students demonstrated increased participation, collaborative engagement, analytical discussion, and confidence in communicating mathematical ideas during learning activities. These findings suggest that Problem-Based Learning can create a more inquiry-oriented and cognitively engaging mathematics learning environment that supports the development of higher-order mathematical thinking and reflective problem-solving skills.

INTRODUCTION

Mathematical problem-solving ability is recognized as one of the most essential competencies in mathematics education because it reflects students' capacity to interpret problems, formulate strategic solutions, apply mathematical concepts systematically, and evaluate the validity of obtained results. Problem solving is not limited to procedural computation; rather, it involves analytical reasoning, conceptual understanding, logical argumentation, and reflective thinking throughout the solution process. Students with strong mathematical problem-solving ability tend to demonstrate greater cognitive flexibility in connecting mathematical ideas, selecting efficient strategies, and adapting prior knowledge to unfamiliar situations (Xu & Qi, 2022; Fatmasari et al., 2021). Moreover, mathematical problem solving is closely associated with higher-order thinking

because students are required not only to produce numerical answers but also to justify reasoning processes, analyze relationships among concepts, and evaluate the consistency of their solutions (Susanti & Hartono, 2019; Ukobizaba et al., 2021). Therefore, the development of mathematical problem-solving ability has become a central objective in contemporary mathematics learning.

Despite its importance, numerous studies indicate that students' mathematical problem-solving ability remains relatively low across various educational contexts. Students frequently experience difficulties understanding problem structures, identifying relevant information, selecting appropriate strategies, and constructing mathematical models systematically (Yuristia & Musdi, 2020; Kusumadewi & Retnawati, 2020). Similar findings were also reported by Ernawati and Sutiarmo (2020), who revealed that students encounter substantial obstacles at each stage of Polya's problem-solving process, particularly in planning solution strategies and evaluating final results. Furthermore, Prabawanto et al. (2024) emphasized that students often fail to transform contextual problems into formal mathematical representations, indicating weaknesses in conceptual interpretation and analytical reasoning. These findings suggest that students' difficulties are not merely computational in nature but are rooted in limited conceptual understanding and insufficient metacognitive awareness during mathematical activity.

The persistence of these difficulties is closely related to the characteristics of classroom instruction that still prioritize procedural learning and teacher-centered practices. In many mathematics classrooms, learning activities remain dominated by one-way explanation and repetitive exercises that encourage memorization rather than conceptual exploration. Such instructional conditions potentially create procedural dependency, where students rely heavily on previously demonstrated examples and struggle to solve problems that differ from routine patterns. Jonsson et al. (2020) argued that meaningful mathematical understanding develops when students are involved in creative mathematical reasoning rather than mechanical procedural imitation. Similarly, Dong et al. (2019) found that student-centered learning environments provide stronger cognitive engagement compared to teacher-dominated instruction because students actively construct understanding through interaction and inquiry. More recently, Xia (2026) emphasized that passive learning environments reduce students' proactive cognitive participation and limit the development of adaptive reasoning processes necessary for complex problem solving. Consequently, mathematics instruction that overemphasizes procedural transmission may inhibit the growth of analytical reasoning, reflective judgment, and independent problem-solving ability.

These instructional issues were also identified during preliminary observations and interviews conducted with mathematics teachers at SMAN 19 Pekanbaru. Teachers reported that students frequently encountered difficulties identifying information contained in mathematical problems, especially when the problems differed from examples previously demonstrated during instruction. Students tended to imitate procedural steps mechanically without understanding the underlying mathematical relationships. As a result, many students were unable to formulate independent solution strategies or provide logical explanations for their answers when confronted with non-routine problems. Furthermore, students rarely re-evaluated the correctness of their solutions after obtaining final answers, indicating weak reflective and metacognitive processes during problem solving. This condition aligns with the findings of Arum et al. (2019), who stated that metacognitive awareness substantially influences students' ability to monitor, regulate, and evaluate mathematical reasoning processes. Likewise, Çini et al. (2023) emphasized that reflective awareness and self-regulation play significant roles in collaborative problem-solving performance because students who possess stronger metacognitive control tend to evaluate solution accuracy more critically.

Classroom observations further revealed that mathematics learning activities were still predominantly teacher-centered, with teachers assuming the dominant role in delivering material while students acted mainly as passive recipients of information. During classroom interaction, students rarely expressed mathematical ideas, responded critically to explanations, or participated actively in discussion activities. Such conditions indicate limited cognitive engagement and insufficient opportunities for students to develop mathematical discourse and analytical reasoning. In addition, instructional activities were largely focused on routine exercises with repetitive solution structures, resulting in minimal exposure to contextual or non-routine problems that require strategic thinking and conceptual interpretation. These findings reinforce the argument that existing instructional practices have not yet optimally facilitated the development of higher-order mathematical thinking skills.

To strengthen the empirical basis of these observations, a preliminary test was administered to evaluate students' mathematical problem-solving ability based on four indicators adapted from Polya's problem-solving stages, namely understanding the problem, planning the solution, carrying out the solution, and checking back. The results are presented in Table 1.

Table 1. Average Mathematical Problem-Solving Ability of Grade XI-2 Students in the Initial Test

No	Problem-Solving Indicator	Average Score
1	Understanding the problem	44.29
2	Planning the solution	31.09
3	Carrying out the solution	40.23
4	Checking back	10.97

Table 1 demonstrates that students' mathematical problem-solving ability remained low across all indicators. The weakest performance occurred in the checking back indicator, with an average score of only 10.97, indicating that students rarely verified the validity, relevance, or logical consistency of their solutions. Analytically, this finding is highly significant because reflective evaluation constitutes an essential component of metacognitive reasoning and higher-order mathematical thinking. Students' inability to revisit and justify obtained answers suggests that their mathematical activity remains concentrated at the procedural execution stage rather than extending toward reflective and analytical reasoning. This finding is consistent with Akben (2020), who emphasized that metacognitive awareness significantly contributes to students' capacity to evaluate and regulate problem-solving processes. Similarly, Junaedi and Wahyudin (2020) argued that reflective thinking skills are crucial for strengthening students' reasoning quality and conceptual understanding in mathematics learning.

The low achievement in the planning indicator also indicates that students experienced considerable difficulty transforming problem information into coherent mathematical strategies. Many students were unable to determine relevant concepts, formulate mathematical models, or organize systematic procedures independently. Effendi and Sitompul (2023) similarly found that students frequently experience difficulties selecting appropriate strategies and connecting mathematical concepts during problem-solving activities. These findings indicate that students' weaknesses extend beyond computational errors and involve broader deficiencies in conceptual understanding, strategic reasoning, and analytical interpretation.

Considering these conditions, instructional improvement becomes necessary to reconstruct mathematics learning into a more cognitively engaging and problem-oriented environment. One instructional approach considered highly relevant for addressing these challenges is Problem Based Learning (PBL). PBL emphasizes learning through authentic problem situations that encourage students to investigate, analyze information, formulate hypotheses, evaluate alternative strategies, and communicate reasoning collaboratively. Through problem-oriented activities, students are positioned as active constructors of knowledge rather than passive recipients of procedural information. Tama et al. (2020) explained that PBL facilitates the development of higher-order thinking skills because students are continuously involved in analytical inquiry and reflective reasoning throughout learning activities. Likewise, Siagan et al. (2019) found that learning materials oriented toward PBL effectively improved both mathematical problem-solving ability and metacognitive awareness among students.

The characteristics of PBL strongly align with the cognitive demands of mathematical problem solving because students are encouraged to understand problems critically, construct solution plans systematically, evaluate obtained results, and reflect on reasoning processes collaboratively. In addition, problem-oriented learning environments potentially create greater cognitive engagement and more meaningful conceptual understanding compared to conventional procedural instruction. Nugraheni and Marsigit (2021) similarly demonstrated that contextual and student-centered mathematics learning contributes positively to the improvement of problem-solving ability because students actively connect mathematical concepts with authentic situations. Therefore, the implementation of PBL is expected to transform mathematics learning from procedural repetition into analytical exploration and reflective inquiry, thereby improving students' mathematical problem-solving ability, reasoning quality, and metacognitive awareness among Grade XI-2 students at SMAN 19 Pekanbaru.

METHOD

This study employed a collaborative Classroom Action Research (CAR) design to improve students' mathematical problem-solving ability through the implementation of the Problem-Based Learning (PBL) model in mathematics instruction. The study adopted a cyclical and reflective inquiry approach because Classroom Action Research enables researchers and practitioners to collaboratively identify classroom learning problems, implement pedagogical interventions, evaluate instructional effectiveness, and continuously refine teaching practices based on empirical reflection (Nurhasanah et al., 2020). The collaborative approach was considered appropriate because the improvement of mathematical problem-solving ability requires systematic pedagogical reconstruction grounded in authentic classroom contexts rather than experimental manipulation under controlled conditions. Furthermore, collaborative action research emphasizes reflective professional practice in which teachers and researchers jointly analyze instructional challenges, evaluate pedagogical decisions, and redesign learning strategies through continuous reflective cycles (Qing-li et al., 2019). In this study, the researcher collaborated with the mathematics teacher of Grade XI-2 at SMAN 19 Pekanbaru, Mrs. Yeyen Vioskha, M.Pd., throughout the stages of planning, implementation, observation, reflection, and instructional redesign.

The study was conducted in Grade XI-2 of SMAN 19 Pekanbaru during the odd semester of the 2025/2026 academic year. The participants consisted of 41 students, comprising 18 male

students and 23 female students. The class was purposively selected based on preliminary observations, interviews with the mathematics teacher, and initial diagnostic test results indicating low mathematical problem-solving performance, limited student participation during mathematics learning, and students' difficulties in solving non-routine mathematical problems. In addition, students demonstrated a strong tendency toward procedural dependency, where solution strategies relied heavily on previously demonstrated examples rather than analytical reasoning and conceptual understanding. These characteristics made the class relevant for investigating the implementation of PBL as an instructional intervention intended to enhance higher-order mathematical thinking and reflective problem-solving processes.

The research consisted of two action cycles, with each cycle involving four interconnected stages: planning, action implementation, observation, and reflection. The cyclical structure was designed to facilitate continuous instructional improvement through reflective evaluation of learning practices implemented in each cycle. During the planning stage, the researcher and collaborating teacher jointly designed lesson plans based on the syntax of the Problem-Based Learning model, prepared student worksheets, designed contextual mathematical problems, developed observation instruments, and constructed mathematical problem-solving tests aligned with Polya's problem-solving indicators. The learning activities were structured to encourage students to analyze contextual problems, formulate solution strategies collaboratively, communicate mathematical reasoning, and evaluate the validity of obtained solutions.

During the implementation stage, the learning process was conducted using the Problem-Based Learning model. The implementation of PBL followed several instructional phases, including problem orientation, collaborative investigation, strategy development, presentation of solutions, and reflective evaluation. At the beginning of learning activities, students were presented with contextual mathematical problems designed to stimulate analytical thinking and conceptual interpretation. Students then worked collaboratively in small groups to identify relevant information, formulate mathematical models, discuss alternative solution strategies, and justify their reasoning processes. During classroom discussions, the teacher functioned primarily as a facilitator who guided inquiry processes, encouraged mathematical argumentation, and supported reflective questioning rather than directly transmitting procedural solutions. At the end of each learning session, students were encouraged to evaluate the accuracy and relevance of their solutions through reflective discussion activities.

The observation stage was conducted simultaneously during the implementation of learning activities. Classroom observations focused on students' participation, collaborative interaction, engagement in mathematical reasoning, problem-solving behavior, and the implementation quality of the PBL model. Observations were carried out collaboratively by the researcher and the mathematics teacher using structured observation sheets accompanied by reflective field notes. The use of collaborative observation was intended to increase data credibility and minimize subjective interpretation during the evaluation of classroom interactions and learning processes.

The reflection stage constituted a central component of the Classroom Action Research process because it functioned as the basis for pedagogical reconstruction in the subsequent

cycle. After each cycle, the researcher and collaborating teacher analyzed the implementation outcomes, identified instructional weaknesses, evaluated students' responses to learning activities, and discussed obstacles encountered during the learning process. The reflective analysis also focused on identifying deficiencies in students' mathematical problem-solving performance across each problem-solving indicator. The findings obtained during the reflection stage were subsequently used to redesign learning strategies, improve classroom interaction patterns, strengthen scaffolding during group discussion, and refine contextual problem characteristics implemented in the following cycle. Thus, the second cycle represented an instructional improvement process grounded in empirical reflection from the first cycle rather than a mere repetition of learning activities.

Data collection techniques in this study consisted of observation and mathematical problem-solving ability tests. Observation data were collected using structured observation sheets designed to document students' participation, collaborative interaction, engagement during problem-solving activities, and responsiveness toward reflective questioning during the implementation of PBL. To strengthen the trustworthiness of observational findings, classroom observations were complemented by reflective field notes documenting instructional dynamics and students' behavioral responses throughout the learning process.

The mathematical problem-solving ability test was administered at the initial stage, at the end of Cycle I, and at the end of Cycle II to evaluate the progression of students' problem-solving performance. The test instrument consisted of descriptive mathematical problems developed based on four indicators adapted from Polya's problem-solving framework, namely understanding the problem, planning the solution, carrying out the solution, and checking back. The use of descriptive problems was intended to explore students' reasoning processes, strategic thinking, and reflective evaluation more comprehensively than objective testing formats. Instrument development was aligned with the learning objectives and indicators of mathematical problem-solving ability to ensure content relevance and construct representation.

Prior to implementation, the test instrument and scoring rubric were reviewed by mathematics education experts to ensure content validity, conceptual alignment, and clarity of problem representation. The scoring rubric for mathematical problem-solving ability was adapted from Damayanti and Kartini (2022), with several modifications to align the rubric with the characteristics of contextual mathematical problems used in this study. The rubric assessed students' performance across four dimensions of mathematical problem solving: understanding the problem, planning the solution, implementing the solution strategy, and reflective verification of answers.

Table 2. Mathematical Problem-Solving Ability Scoring Rubric

Assessed Aspect	Score	Indicator
Understanding the problem	0	Does not identify known and asked information
	1	Identifies either known or asked information incompletely
	2	Identifies known and asked information but inaccurately
	3	Correctly identifies known and asked information

Planning the solution	0	Does not formulate a solution strategy
	1	Formulates an inaccurate or incomplete strategy
	2	Formulates an appropriate solution strategy
Implementing the solution	0	Does not provide a solution
	1	Provides incorrect or minimally correct procedures
	2	Provides partially correct procedures
	3	Provides complete and correct procedures
Checking back	0	Does not provide reflective evaluation
	1	Provides incomplete or inaccurate conclusion
	2	Provides accurate reflective conclusion

Students' mathematical problem-solving performance was subsequently categorized using the qualification criteria presented in Table 3.

Table 3. Qualification Criteria for Mathematical Problem-Solving Ability

Score Interval	Qualification
85–100	Very Good
70–84.99	Good
55–69.99	Fair
40–54.99	Poor
0–39.99	Very Poor

Data analysis was conducted quantitatively and qualitatively. Quantitative analysis was used to examine the progression of students' mathematical problem-solving ability across the initial test, Cycle I, and Cycle II by calculating average scores for each problem-solving indicator and the overall class performance. Improvements in mathematical problem-solving ability were identified based on increases in indicator achievement, average class scores, and the proportion of students achieving good and very good qualification categories in each cycle. Meanwhile, qualitative analysis was conducted on observation results and reflective field notes to examine changes in students' participation, collaborative reasoning, problem-solving behavior, and engagement during the implementation of PBL. The integration of quantitative and qualitative findings enabled a more comprehensive interpretation of instructional improvement and students' cognitive development throughout the action research process.

The success criteria of this study were determined based on both process-oriented and outcome-oriented indicators. From the process perspective, instructional improvement was considered successful if students demonstrated increased participation in collaborative discussion, greater engagement in analytical reasoning, and more active involvement in reflective problem-solving activities during mathematics learning. From the outcome perspective, improvement was identified if the average mathematical problem-solving score increased consistently across cycles, if each problem-solving indicator showed positive

progression, and if the proportion of students achieving good and very good qualification categories increased substantially from the initial condition to the end of Cycle II. This study also considered research ethics throughout the implementation process. Permission to conduct the study was obtained from the school administration and the collaborating mathematics teacher. Students' identities were treated confidentially, and all collected data were used exclusively for academic and research purposes.

RESULT

Results of Teacher and Student Activity Analysis

The analysis of teacher and student activities was conducted using observation sheets and reflective field notes collected during the implementation of the Problem-Based Learning (PBL) model across two action cycles. The analysis focused on examining the progression of classroom interaction quality, students' cognitive engagement, collaborative participation, and reflective problem-solving behavior throughout the intervention process. The findings indicate that the implementation of PBL gradually transformed the learning environment from predominantly procedural and teacher-centered instruction toward more active, inquiry-oriented, and collaborative mathematical learning.

During the introductory activities in Cycle I, the classroom management process was generally implemented effectively. Students responded to greetings, prepared learning materials, and followed classroom routines in an orderly manner. The teacher also communicated the learning objectives, motivational orientation, and the sequence of learning activities. However, students' cognitive engagement during the initial stage remained uneven. Only several students actively responded to the teacher's questions and explanations, while most students still demonstrated passive participation patterns. Furthermore, group organization activities required relatively long transition time because students were not yet accustomed to collaborative learning structures. Many students tended to interact socially rather than engage immediately in academic discussion, indicating limited familiarity with inquiry-oriented group learning environments.

Reflective analysis conducted after Cycle I identified several instructional deficiencies that potentially inhibited the effectiveness of collaborative problem-solving activities. These deficiencies included students' low confidence in expressing mathematical ideas, limited participation during group discussions, weak problem interpretation skills, and students' dependency on peers' answers during task completion. Based on these findings, several instructional improvements were implemented in Cycle II, including clearer group role allocation, more structured questioning strategies, intensified teacher scaffolding during discussion activities, and explicit encouragement for students to communicate reasoning processes during collaborative work.

The implementation of these reflective improvements contributed to substantial changes in classroom interaction patterns during Cycle II. Students became more actively involved in learning activities and demonstrated greater readiness to participate in collaborative discussions. Group organization activities also became significantly more efficient because students had adapted to the collaborative learning structure established during the previous cycle. More importantly, students demonstrated increased confidence in expressing mathematical ideas, responding to questions, and participating in analytical discussion activities. These findings indicate that the iterative implementation of PBL gradually strengthened students' cognitive engagement and reduced passive learning tendencies that had previously characterized classroom instruction.

Substantial improvement was also identified during the core learning activities. In Cycle I, many students experienced difficulties interpreting contextual mathematical problems and identifying relevant information required for solution construction. Students tended to wait for direct procedural guidance from peers or the teacher rather than independently constructing mathematical reasoning. Collaborative discussions also remained relatively superficial because students focused primarily on obtaining answers rather than analyzing alternative solution strategies. These findings suggest that students initially experienced procedural dependency and limited exposure to reflective mathematical reasoning practices.

Following instructional refinement in Cycle II, students demonstrated more analytical and independent problem-solving behavior. Most students were able to identify relevant information from contextual problems, formulate mathematical models more systematically, and participate actively in collaborative reasoning processes. Students also became more willing to ask questions and provide argumentative responses during classroom discussions. The improvement in collaborative inquiry patterns indicates that the implementation of PBL successfully encouraged students to engage more deeply in analytical interpretation and strategic reasoning activities rather than relying exclusively on procedural imitation.

Improvement was similarly observed during the closing activities of the learning process. In the early implementation of Cycle I, only a small number of students voluntarily communicated conclusions or participated in reflective discussion activities. Most students still demonstrated hesitation when evaluating learning outcomes or expressing reflective judgments regarding problem-solving processes. However, in Cycle II, student participation in reflective activities increased substantially. More students actively communicated conclusions, evaluated obtained solutions, and responded to reflective questions posed by the teacher. These findings indicate gradual improvement in students' reflective thinking and metacognitive awareness during mathematical learning activities.

The reflective evaluation conducted after Cycle I also identified time-management limitations during formative assessment activities. In the first meeting of Cycle I, formative assessment could not be administered due to insufficient instructional time allocation, while in the second meeting, the assessment process was not completed optimally. To address these issues, the instructional design in Cycle II was revised by improving time allocation management and structuring assessment activities more systematically. As a result, formative assessment activities in Cycle II were implemented more effectively, and students completed the tasks independently within the allocated instructional time. To clarify the progression of classroom interaction and students' cognitive engagement during the implementation of PBL, the summary of observational findings across cycles is presented in Table 4.

Table 4. Development of Teacher and Student Learning Activities Across Cycles

Observation Aspect	Cycle I	Cycle II
Student participation	Limited and uneven	More active and evenly distributed
Group collaboration	Inefficient and socially dominated	Structured and academically focused
Problem interpretation	Students experienced difficulty identifying relevant information	Students identified problems more systematically

Mathematical discussion	Procedural and answer-oriented	Analytical and reasoning-oriented
Student confidence	Hesitant to ask questions or express ideas	More confident in communicating reasoning
Reflective participation	Limited reflective response	Increased reflective engagement
Classroom management	Transition activities consumed substantial time	Learning activities became more efficient

The findings presented in Table 4 demonstrate that the implementation of PBL contributed not only to quantitative improvement in mathematical problem-solving performance but also to qualitative transformation in classroom learning culture. The progression from passive participation toward collaborative inquiry and reflective reasoning indicates that students gradually developed stronger cognitive engagement throughout the intervention process.

Results of Mathematical Problem-Solving Ability Analysis

Students' mathematical problem-solving ability was analyzed based on the results of the initial test, Cycle I test, and Cycle II test. The analysis focused on four indicators adapted from Polya's problem-solving framework, namely understanding the problem, planning the solution, carrying out the solution, and checking back. The results of the indicator-level analysis are presented in Table 5.

Table 5. Average Mathematical Problem-Solving Ability Scores Across Indicators

No	Problem-Solving Indicator	Initial Test	Cycle I	Cycle II
1	Understanding the problem	44.29	66.22	71.94
2	Planning the solution	31.09	69.50	75.60
3	Carrying out the solution	40.23	79.26	81.70
4	Checking back	10.97	51.21	60.97

Table 5 demonstrates consistent improvement across all indicators of mathematical problem-solving ability from the initial condition to Cycle II. The findings indicate that the implementation of PBL positively contributed to students' capacity to interpret mathematical problems, formulate strategic solution plans, execute mathematical procedures systematically, and evaluate obtained results reflectively. The most substantial improvement occurred in the planning indicator, which increased from 31.09 in the initial test to 75.60 in Cycle II. This finding suggests that students became increasingly capable of organizing mathematical information, selecting appropriate strategies, and constructing coherent solution pathways throughout the implementation of PBL. The improvement can be associated with collaborative investigation activities during PBL, where students were continuously encouraged to analyze contextual problems, discuss alternative approaches, and justify strategic decisions collectively.

Similarly, the carrying out the solution indicator demonstrated significant improvement, increasing from 40.23 to 81.70. This result indicates that students became more capable of implementing mathematical procedures accurately and systematically after participating in collaborative problem-solving activities. The repeated exposure to analytical discussion and guided

reasoning processes during PBL likely strengthened students' procedural accuracy and conceptual understanding simultaneously. The understanding the problem indicator also showed substantial improvement, increasing from 44.29 to 71.94. Although some students still experienced difficulties interpreting contextual information precisely, most students demonstrated stronger ability to identify known and required information systematically in Cycle II. This finding indicates that contextual problem orientation in PBL contributed positively to students' interpretative reasoning processes.

The checking back indicator remained the lowest-performing indicator despite showing the most dramatic relative improvement, increasing from 10.97 to 60.97. This finding is analytically important because reflective evaluation constitutes a higher-order cognitive process closely associated with metacognitive awareness and reflective reasoning. The substantial increase suggests that students gradually developed greater awareness of the importance of verifying solution validity and evaluating the consistency of obtained answers. However, the comparatively lower score compared to other indicators indicates that reflective verification remained cognitively challenging for several students, particularly those who were still accustomed to procedural completion without evaluative reflection. To provide clearer interpretation regarding the magnitude of improvement across indicators, the percentage increase from the initial test to Cycle II is presented in Table 6.

Table 6. Percentage Increase in Mathematical Problem-Solving Indicators

Problem-Solving Indicator	Initial Test	Cycle II	Percentage Increase
Understanding the problem	44.29	71.94	62.43%
Planning the solution	31.09	75.60	143.16%
Carrying out the solution	40.23	81.70	103.08%
Checking back	10.97	60.97	455.79%

Table 6 demonstrates that the most substantial relative increase occurred in the checking back indicator. Although reflective evaluation remained the weakest aspect overall, the dramatic improvement indicates that the implementation of PBL successfully strengthened students' reflective reasoning and metacognitive engagement during mathematical problem-solving activities. Further analysis was conducted to examine the distribution of students' mathematical problem-solving qualifications across cycles. The results are presented in Table 7.

Table 7. Distribution of Mathematical Problem-Solving Ability Qualifications

Score Interval	Initial Test	Cycle I	Cycle II	Qualification
85–100	1 (2.43%)	17 (41.46%)	18 (43.90%)	Very Good
70–84.99	1 (2.43%)	6 (14.63%)	9 (21.95%)	Good
55–69.99	1 (2.43%)	2 (4.87%)	4 (9.75%)	Fair
40–54.99	15 (36.58%)	8 (19.51%)	6 (14.63%)	Poor
0–39.99	23 (56.09%)	8 (19.51%)	4 (9.75%)	Very Poor

Table 7 indicates substantial improvement in the distribution of students' mathematical problem-solving qualifications. The proportion of students categorized as very good and good

increased significantly across cycles, while the proportion of students classified in poor and very poor categories decreased substantially. Prior to the intervention, most students were concentrated in the very poor qualification category, indicating severe limitations in mathematical reasoning and problem-solving performance. However, by the end of Cycle II, most students had shifted toward higher qualification categories, suggesting meaningful improvement in analytical reasoning, strategic problem solving, and reflective mathematical thinking. Classical improvement in students' mathematical problem-solving ability was further analyzed using average class scores across cycles, as presented in Table 8.

Table 8. Classical Improvement in Mathematical Problem-Solving Ability

Assessment Stage	Average Score	Improvement
Initial Test	33.90	–
Cycle I	67.80	33.90
Cycle II	73.41	5.61

Table 8 demonstrates consistent improvement in students' mathematical problem-solving ability at the class level throughout the intervention process. The average score increased substantially from 33.90 in the initial condition to 67.80 in Cycle I, followed by further improvement to 73.41 in Cycle II. The substantial increase observed in Cycle I indicates that the implementation of PBL immediately contributed to the reconstruction of students' mathematical reasoning processes and problem-solving engagement. Meanwhile, the continued improvement in Cycle II suggests that reflective instructional refinement and increased student adaptation to collaborative inquiry activities further strengthened the effectiveness of the intervention. Overall, the findings indicate that the implementation of the Problem-Based Learning model contributed positively to the improvement of students' mathematical problem-solving ability both quantitatively and qualitatively. The improvement was reflected not only in increased scores across all problem-solving indicators but also in the transformation of classroom interaction patterns, students' analytical participation, collaborative reasoning, and reflective engagement during mathematics learning activities

DISCUSSION

The findings of this study demonstrate that the implementation of the Problem-Based Learning (PBL) model contributed positively to the improvement of students' mathematical problem-solving ability across all indicators of Polya's problem-solving framework, namely understanding the problem, planning the solution, carrying out the solution, and checking back. The improvement was reflected not only in increased quantitative achievement but also in the transformation of students' cognitive engagement, collaborative participation, reflective reasoning, and mathematical interaction patterns throughout the learning process. These findings reinforce the argument that mathematical problem solving is a multidimensional cognitive activity involving conceptual understanding, analytical reasoning, strategic thinking, and reflective evaluation rather than merely procedural execution (Liljedahl & Santos-Trigo, 2019). In this context, the improvement of mathematical problem-solving ability appears to be closely associated with the reconstruction of the learning environment into a more inquiry-oriented, student-centered, and cognitively engaging instructional context.

Prior to the intervention, students demonstrated strong procedural dependency characterized by reliance on memorized examples, limited strategic flexibility, and difficulties interpreting contextual mathematical problems. Most students tended to imitate procedural steps demonstrated by the teacher without sufficiently understanding the conceptual relationships underlying problem structures. Such conditions indicate that the initial instructional environment had not yet facilitated analytical reasoning and independent mathematical inquiry optimally. This finding aligns with Hiebert (2020), who emphasized that procedural learning frequently produces superficial mathematical understanding when students are trained primarily to replicate algorithms without conceptual interpretation. Similarly, Cole (2020) argued that procedural learning environments often limit learners' capacity to engage in adaptive reasoning because learning activities become concentrated on routine reproduction rather than analytical exploration. Consequently, students may demonstrate procedural fluency in familiar situations while remaining unable to transfer knowledge flexibly to unfamiliar or contextualized problems.

The implementation of PBL gradually transformed the orientation of mathematics learning from procedural transmission toward collaborative inquiry and analytical exploration. During the intervention process, students were continuously encouraged to interpret contextual problems, identify relevant information, formulate mathematical models, discuss alternative solution pathways, and evaluate the validity of obtained solutions collaboratively. Such instructional characteristics appear to have strengthened students' cognitive engagement because students were positioned as active constructors of mathematical understanding rather than passive recipients of procedural information. This finding supports inquiry-based mathematics learning perspectives emphasizing that mathematical understanding develops more effectively when students actively investigate, discuss, and justify mathematical ideas through collaborative inquiry processes (Beswick, 2021). Similarly, Kuster et al. (2019) explained that inquiry-oriented instructional environments contribute substantially to the development of analytical reasoning because students are continuously involved in exploratory and meaning-making activities during learning.

The improvement in classroom interaction patterns observed during Cycle II further demonstrates that repeated exposure to inquiry-oriented learning activities contributed positively to students' confidence in expressing mathematical ideas and participating in analytical discussion activities. Initially, students demonstrated hesitation when communicating reasoning processes or responding to reflective questions during group discussion. However, following reflective instructional refinement, students became more willing to engage in collaborative reasoning, communicate arguments, and evaluate alternative solution strategies critically. These findings are consistent with Gómez-Chacón et al. (2024), who found that inquiry-based mathematics education positively influences students' engagement and attitudes toward mathematical learning because students become more actively involved in constructing understanding through interactive learning experiences. The findings also indicate that inquiry-oriented instruction potentially creates a more intellectually productive classroom culture by encouraging students to participate in mathematical discourse rather than functioning merely as passive learners.

One of the most significant findings of this study concerns the substantial improvement in the planning indicator. Prior to the intervention, students experienced considerable difficulty transforming problem information into coherent mathematical strategies. Many students were unable to organize relationships among variables, identify appropriate concepts, or construct systematic solution pathways independently. However, after the implementation of PBL, students demonstrated stronger strategic reasoning and greater flexibility in formulating mathematical plans collaboratively. This finding suggests that collaborative investigation activities within PBL

provided important opportunities for students to negotiate meaning, evaluate alternative strategies, and construct shared mathematical understanding collectively. Daniels et al. (2022) similarly argued that problem-solving progression develops through repeated engagement in increasingly complex reasoning processes that facilitate knowledge transfer and strategic flexibility. Furthermore, Ye et al. (2025) emphasized that learner-centered problem-solving environments encourage students to construct solution pathways more independently because instructional interaction focuses on exploratory reasoning rather than direct procedural guidance.

Substantial improvement was also identified in students' ability to implement solution procedures systematically and accurately. This finding indicates that conceptual understanding and procedural fluency developed simultaneously during collaborative problem-solving activities. Through repeated engagement with contextual mathematical problems, students became increasingly capable of connecting conceptual interpretation with procedural execution. This result supports the perspective that meaningful procedural competence emerges more effectively when mathematical procedures are embedded within analytical reasoning processes rather than isolated repetitive drill practices (Hiebert, 2020). In this study, collaborative discussion activities appear to have strengthened students' ability to justify procedural decisions and apply mathematical operations more systematically because students were required to communicate and defend their reasoning during problem-solving processes.

Another analytically important finding concerns the substantial improvement in the checking back indicator, which demonstrated the largest relative increase among all problem-solving indicators. Initially, most students tended to terminate problem-solving activities immediately after obtaining numerical answers without verifying the consistency or appropriateness of their solutions. Such tendencies indicate weak reflective reasoning and limited metacognitive regulation during mathematical activity. However, through reflective discussion activities embedded within PBL, students gradually developed greater awareness regarding the importance of evaluating solution validity and reconsidering obtained results critically. This finding indicates that PBL contributed not only to conceptual and procedural development but also to the strengthening of reflective mathematical thinking and metacognitive engagement.

The improvement in reflective verification skills may be associated with the implementation of scaffolding and reflective questioning strategies during collaborative learning activities. Dassa et al. (2024) emphasized that scaffolding-metacognitive strategies contribute significantly to students' capacity to regulate reasoning processes, evaluate solution quality, and monitor conceptual understanding during mathematics learning. Similarly, Carreira et al. (2020) argued that analytical reasoning develops through opportunities for students to engage in deductive interpretation and reflective evaluation during problem-solving activities. In this study, the repeated practice of discussing, justifying, and re-evaluating mathematical solutions appears to have strengthened students' reflective awareness progressively, although reflective verification remained cognitively demanding for several students by the end of Cycle II.

The effectiveness of PBL in this study was also strongly associated with the quality of collaborative interaction established during learning activities. Initially, group discussions remained relatively procedural and answer-oriented because students were unfamiliar with inquiry-oriented mathematical communication. However, following instructional refinement, collaborative discussions became more analytical and argumentative in nature. Students increasingly communicated reasoning processes, challenged alternative strategies, and justified mathematical decisions during group interaction. These findings support Lloyd and Murphy's (2023) argument that small-group mathematical discussion activities play an important role in

strengthening mathematical argumentation and conceptual reasoning because students are required to negotiate and defend mathematical ideas collectively. Similarly, Corneli et al. (2019) emphasized that mathematical argumentation constitutes a central component of meaningful mathematical reasoning because argumentation enables students to evaluate claims, justify procedures, and construct logically coherent explanations during mathematical activity.

The reflective structure of Classroom Action Research also contributed significantly to the effectiveness of the intervention. The cyclical process of planning, implementation, observation, reflection, and instructional redesign enabled continuous pedagogical refinement based on empirical classroom evidence. Consequently, the improvement observed in Cycle II was not merely the result of repeated exposure to learning activities but rather the outcome of systematic instructional reconstruction grounded in reflective inquiry. This finding reinforces the argument that reflective and collaborative pedagogical practices are essential for improving instructional effectiveness because sustainable classroom improvement depends on educators' ability to analyze learning processes critically and redesign instructional strategies responsively. In this context, collaborative reflective inquiry enabled both the researcher and teacher to identify classroom weaknesses more systematically and implement targeted instructional modifications throughout the intervention process.

From a broader pedagogical perspective, the findings of this study suggest that improving students' mathematical problem-solving ability requires more than increasing procedural practice frequency or exercise intensity. Instead, meaningful improvement appears to depend on the creation of inquiry-oriented learning environments that simultaneously facilitate analytical reasoning, collaborative inquiry, reflective discussion, and metacognitive engagement. Ulandari et al. (2019) similarly found that contextual and student-centered mathematics learning environments contribute positively to students' mathematical problem-solving ability because students become actively involved in constructing conceptual understanding through authentic mathematical experiences. The findings of this study therefore reinforce the view that mathematics learning becomes more meaningful when students are encouraged to analyze, discuss, justify, and reflect upon mathematical ideas collaboratively rather than merely reproduce procedural algorithms.

Despite the positive findings, several limitations should also be acknowledged. Although substantial improvement was observed across all indicators, some students continued to experience difficulties in reflective verification and strategic reasoning by the end of Cycle II. This finding suggests that the development of higher-order mathematical thinking and metacognitive awareness requires sustained exposure to reflective and inquiry-oriented learning experiences beyond short-term intervention cycles. In addition, emotional factors such as confusion, hesitation, and frustration during complex problem-solving activities may also influence students' reasoning performance and participation patterns during collaborative inquiry processes. Di Leo et al. (2019) explained that emotional experiences play a substantial role in mathematical problem solving because cognitive confusion and frustration may either stimulate deeper reasoning or inhibit students' engagement depending on how instructional support is provided. Therefore, future studies may consider exploring the interaction between emotional regulation, collaborative inquiry, and metacognitive development within mathematics learning contexts more comprehensively.

Overall, the findings of this study demonstrate that the implementation of Problem-Based Learning within a collaborative Classroom Action Research framework contributed positively to improving students' mathematical problem-solving ability, reflective reasoning, collaborative engagement, and analytical mathematical thinking. The integration of contextual problem

orientation, collaborative inquiry, reflective discussion, metacognitive scaffolding, and cyclical pedagogical refinement created a learning environment that supported the development of higher-order mathematical cognition more effectively than conventional procedural instruction. Consequently, Problem-Based Learning may be considered a pedagogically relevant approach for strengthening students' analytical, reflective, and inquiry-oriented mathematical competencies within secondary mathematics education contexts.

CONCLUSIONS

The findings of this study indicate that the implementation of the Problem-Based Learning (PBL) model contributed positively to improving both the mathematics learning process and students' mathematical problem-solving ability in Grade XI-2 of SMAN 19 Pekanbaru during the odd semester of the 2025/2026 academic year. The improvement was reflected in the progression of all mathematical problem-solving indicators, including understanding the problem, planning solution strategies, implementing mathematical procedures, and checking back. In addition, the implementation of PBL encouraged greater student participation, collaborative reasoning, reflective engagement, and analytical interaction during mathematics learning activities. The findings also demonstrate that inquiry-oriented and collaborative learning environments can support the development of higher-order mathematical thinking more effectively than procedural and teacher-centered instructional approaches. Through contextual problem-solving activities and reflective discussion processes, students gradually became more capable of constructing mathematical reasoning, communicating ideas, and evaluating the validity of obtained solutions systematically. Despite these positive outcomes, several limitations were identified during the implementation process, particularly regarding instructional time management and students' reflective verification skills. Some students still experienced difficulties in evaluating and rechecking their final solutions consistently, indicating that reflective mathematical thinking requires sustained instructional practice and continuous metacognitive support. Therefore, future studies are recommended to optimize time allocation during collaborative learning activities and provide more structured scaffolding to strengthen students' reflective reasoning and problem-solving evaluation skills.

REFERENCES

- Akben, N. (2020). Effects of the problem-posing approach on students' problem solving skills and metacognitive awareness in science education. *Research in Science Education*, 50(3), 1143–1165. <https://doi.org/10.1007/s11165-018-9726-7>
- Arum, R. P., Widjajanti, D. B., & Retnawati, H. (2019). Metacognitive awareness: How it affects mathematical problem-solving process. *Journal of Physics: Conference Series*, 1320(1), Article 012054. <https://doi.org/10.1088/1742-6596/1320/1/012054>
- Beswick, K. (2021). Inquiry-based approaches to mathematics learning, teaching, and mathematics education research. *Journal of Mathematics Teacher Education*, 24(2), 123–126. <https://doi.org/10.1007/s10857-021-09494-4>
- Carreira, S., Amado, N., & Jacinto, H. (2020). Venues for analytical reasoning problems: How children produce deductive reasoning. *Education Sciences*, 10(6), Article 169. <https://doi.org/10.3390/educsci10060169>
- Çini, A., Järvelä, S., Dindar, M., Malmberg, J., Haataja, E., & Sobocinski, M. (2023). How multiple levels of metacognitive awareness operate in collaborative problem solving. *Metacognition and Learning*, 18(3), 891–922. <https://doi.org/10.1007/s11409-023-09358-7>

- Cole, A. (2020). The trouble with adjectives: Aligning singing tuition and artistic practice with procedural learning theory. *Australian Voice*, 21, 49–56. <https://search.informit.org/doi/10.3316/informit.754896215715506>
- Corneli, J., Martin, U., Murray-Rust, D., Pease, A., & Puzio, R. (2019). Argumentation theory for mathematical argument. *Argumentation*, 33(2), 173–214. <https://doi.org/10.1007/s10503-018-9474-x>
- Daniels, J. S., Moreau, D., & Macnamara, B. N. (2022). Learning and transfer in problem solving progressions. *Journal of Intelligence*, 10(4), Article 85. <https://doi.org/10.3390/jintelligence10040085>
- Dassa, A., Sutamrin, S., Ihsan, H., Naufal, M. A., Nasir, N., & Nurhajarurahmah, S. Z. (2024). The implementation of scaffolding-metacognitive strategies in flipped classroom for mathematics learning. In *Proceedings of the International Conference on Sciences, Technology and Education (ICSTE 2024)* (pp. 102–111). Atlantis Press. https://doi.org/10.2991/978-2-38476-335-1_10
- Di Leo, I., Muis, K. R., Singh, C. A., & Psaradellis, C. (2019). Curiosity... confusion? Frustration! The role and sequencing of emotions during mathematics problem solving. *Contemporary Educational Psychology*, 58, 121–137. <https://doi.org/10.1016/j.cedpsych.2019.03.001>
- Dong, Y., Wu, S. X., Wang, W., & Peng, S. (2019). Is the student-centered learning style more effective than the teacher-student double-centered learning style in improving reading performance? *Frontiers in Psychology*, 10, Article 2630. <https://doi.org/10.3389/fpsyg.2019.02630>
- Effendi, K. N. S., & Sitompul, M. T. (2023). Students' difficulties in solving mathematical problems. In *3rd Borobudur International Symposium on Science and Technology 2021* (Vol. 2706, No. 1, Article 020099). AIP Publishing. <https://doi.org/10.1063/5.0120257>
- Ernawati, & Sutiarto, S. (2020). Analysis of difficulties in solving mathematical problems categorized higher order thinking skills (HOTS) on the subject of rank and shape of the root according to Polya stages. *Journal of Physics: Conference Series*, 1563(1), Article 012041. <https://doi.org/10.1088/1742-6596/1563/1/012041>
- Fatmasari, H. R., Waluya, S. B., & Sugianto. (2021). Mathematical problem-solving ability based on self-efficacy in junior high school. *Journal of Physics: Conference Series*, 1918(4), Article 042120. <https://doi.org/10.1088/1742-6596/1918/4/042120>
- Gómez-Chacón, I. M., Bacelo, A., Marbán, J. M., Romero, I., & Ruiz-Higueras, L. (2024). Inquiry-based mathematics education and attitudes towards mathematics: Tracking profiles for teaching. *Mathematics Education Research Journal*, 36(4), 715–743. <https://doi.org/10.1007/s13394-023-00468-8>
- Hiebert, J. (2020). Mathematical, cognitive, and instructional analyses of decimal fractions. In *Analysis of arithmetic for mathematics teaching* (pp. 283–322). Routledge. <https://doi.org/10.4324/9781315044606-5>
- Jonsson, B., Granberg, C., & Lithner, J. (2020). Gaining mathematical understanding: The effects of creative mathematical reasoning and cognitive proficiency. *Frontiers in Psychology*, 11, Article 574366. <https://doi.org/10.3389/fpsyg.2020.574366>
- Junaedi, Y., & Wahyudin, W. (2020). Improving student's reflective thinking skills through realistic mathematics education approach. In *Proceedings of the 4th Asian Education Symposium (AES 2019)* (pp. 196–202). Atlantis Press. <https://doi.org/10.2991/assehr.k.200513.044>
- Kuster, G., Johnson, E., Rupnow, R., & Schukajlow, S. (2019). The inquiry-oriented instructional

- measure. *International Journal of Research in Undergraduate Mathematics Education*, 5(2), 183–204. <https://doi.org/10.1007/s40753-019-00089-2>
- Kusumadewi, C. A., & Retnawati, H. (2020). Identification of elementary school students' difficulties in mathematical problem-solving. *Journal of Physics: Conference Series*, 1511(1), Article 012031. <https://doi.org/10.1088/1742-6596/1511/1/012031>
- Liljedahl, P., & Santos-Trigo, M. (Eds.). (2019). *Mathematical problem solving*. Springer International Publishing. <https://doi.org/10.1007/978-3-030-10472-6>
- Lloyd, G. M., & Murphy, P. K. (2023). Mathematical argumentation in small-group discussions of complex mathematical tasks in elementary teacher education settings. In R. Leikin (Ed.), *Mathematical challenges for all* (pp. 201–223). Springer. https://doi.org/10.1007/978-3-031-18868-8_9
- Nugraheni, L. P., & Marsigit, M. (2021). Realistic mathematics education: An approach to improve problem solving ability in primary school. *Journal of Education and Learning (EduLearn)*, 15(4), 511–518. <https://doi.org/10.11591/edulearn.v15i4.19354>
- Nurhasanah, F., Sukandi, U., Kuncoro, A. B., Rusilowati, A., Hastuti, W. S., & Prabowo, A. (2020). Collaborative classroom action research for mathematics and science teachers in Indonesia. *Journal of Physics: Conference Series*, 1613(1), Article 012024. <https://doi.org/10.1088/1742-6596/1613/1/012024>
- Prabawanto, S., Herman, T., Melani, R., Samosir, C. M., & Mefiana, S. A. (2024). Students' difficulties in understanding problems and making mathematical models in the contextual problem solving process. In *Proceedings of the 4th International Conference on Education and Technology (ICETECH 2023)* (pp. 796–810). Atlantis Press. https://doi.org/10.2991/978-94-6463-554-6_66
- Qing-li, H., Torres, M. N., & Shi-Ji, F. (2019). Collaborative action research for preparing teachers as reflective practitioners. *Systemic Practice and Action Research*, 32(4), 411–427. <https://doi.org/10.1007/s11213-018-9461-z>
- Siagan, M. V., Saragih, S., & Sinaga, B. (2019). Development of learning materials oriented on problem-based learning model to improve students' mathematical problem solving ability and metacognition ability. *International Electronic Journal of Mathematics Education*, 14(2), 331–340. <https://doi.org/10.29333/iejme/5717>
- Susanti, E., & Hartono. (2019). An analysis mathematical problem solving and mathematical critical thinking skills of junior high school students. *Journal of Physics: Conference Series*, 1320(1), Article 012071. <https://doi.org/10.1088/1742-6596/1320/1/012071>
- Tama, N. S., Aisyah, N., Santoso, B., & Kurniadi, E. (2020). Learning higher-order thinking skills using problem-based learning model. *Journal of Physics: Conference Series*, 1480(1), Article 012008. <https://doi.org/10.1088/1742-6596/1480/1/012008>
- Ukobizaba, F., Nizeyimana, G., & Mukuka, A. (2021). Assessment strategies for enhancing students' mathematical problem-solving skills: A review of literature. *Eurasia Journal of Mathematics, Science and Technology Education*, 17(3), Article em1945. <https://doi.org/10.29333/ejmste/9728>
- Ulandari, L., Amry, Z., & Saragih, S. (2019). Development of learning materials based on realistic mathematics education approach to improve students' mathematical problem solving ability and self-efficacy. *International Electronic Journal of Mathematics Education*, 14(2), 375–383. <https://doi.org/10.29333/iejme/5721>
- Xia, X. (2026). From passive to proactive learning: Adaptive transformation of forgettable causal relationships in entire interactive learning process. *Interactive Learning Environments*, 34(1),

1–30. <https://doi.org/10.1080/10494820.2025.2612253>

- Xu, Z., & Qi, C. (2022). Middle school students' mathematical problem-solving ability and the influencing factors in mainland China. *Frontiers in Psychology, 13*, Article 1042315. <https://doi.org/10.3389/fpsyg.2022.1042315>
- Ye, H., Liang, B., & Ng, O. L. (2025). A learner-centred exploration of teachers' solution pathways in K-12 programming-based mathematical problem-solving. *Journal of Computer Assisted Learning, 41*(5), Article e70102. <https://doi.org/10.1111/jcal.70102>
- Yuristia, N., & Musdi, E. (2020). Analysis of early mathematical problem-solving ability in mathematics learning for junior high school student. *Journal of Physics: Conference Series, 1554*(1), Article 012026. <https://doi.org/10.1088/1742-6596/1554/1/012026>