ESENSI: Jurnal Riset Pendidikan
Vol. 2, No. 1, Desember 2025, pp. 1-11
eISSN 3089-3615 | https://ejournal.gemacendekia.org/index.php/esensi

Optimizing Science Learning through a Problem-Based Approach

Andri Akbar [a,1]*, Rina Asmawati [a,2], Herman Juanda [a,3]

[a] Study Program in Biology Education, State Islamic University of Mataram, Indonesia
[1] andriakbar56@gmail.com*, [2] rinaasmawati98@gmail.com, [3] hermanjuanda97@gmail.com
* Corresponding Author

ABSTRACT

Optimizing science learning requires instructional approaches that promote not only conceptual understanding but also higher-order cognitive skills and active learner engagement. This study examines the effectiveness of a structured Problem-Based Learning (PBL) approach in enhancing science learning outcomes, including conceptual understanding, problem-solving skills, critical thinking ability, and student engagement. A quasi-experimental design with a pretest–posttest non-equivalent control group was employed. Participants consisted of students enrolled in a science course, divided into an experimental group receiving PBL-based instruction and a control group receiving conventional teacher-centered instruction. Data were collected using validated instruments measuring conceptual understanding, problem-solving skills, and critical thinking, complemented by student engagement questionnaires and classroom observations. The results indicate that students in the PBL group achieved significantly higher posttest scores across all measured cognitive domains compared to the control group. Notable improvements were observed in students' ability to apply scientific concepts, analyze complex problems, evaluate evidence, and construct reasoned solutions. In addition, students exposed to PBL demonstrated higher levels of behavioral, cognitive, and emotional engagement during the learning process. Classroom observations revealed that collaborative inquiry, reflection, and active discussion were more prominent in the PBL environment than in conventional instruction. These findings suggest that Problem-Based Learning is an effective pedagogical approach for optimizing science learning outcomes. By engaging students in authentic problem-solving contexts and promoting active knowledge construction, PBL supports deeper understanding and the development of essential scientific skills. The study provides empirical support for the integration of structured PBL models into science education to enhance both learning quality and student engagement.

Article History
Received 2025-10-20
Revised 2025-11-13
Accepted 2025-12-20

Keywords
Problem-Based Learning
Science Learning
Conceptual Understanding
Problem-Solving Skills
Critical Thinking

INTRODUCTION

Science education plays a crucial role in preparing learners to understand natural phenomena, engage in scientific reasoning, and apply knowledge to solve real-world problems. In the context of rapid technological advancement and increasing societal complexity, the goals of science learning have expanded beyond the acquisition of factual knowledge toward the development of higher-order cognitive skills, such as critical thinking, problem-solving, collaboration, and self-directed learning. However, numerous studies have indicated that conventional teacher-centered instructional approaches remain dominant in many science classrooms, often emphasizing rote memorization and procedural understanding rather than conceptual depth and transferable reasoning skills (Marcinauskas et al., 2024; Smith et al., 2022). This mismatch between instructional practices and desired learning outcomes has prompted educators and researchers to seek pedagogical approaches capable of optimizing science learning in a more holistic and meaningful manner.

How to cite: Akbar, A., Asmawati, R. & Juanda, H. (2025). Optimizing Science Learning through a Problem-Based Approach. *ESENSI: Jurnal Riset Pendidikan, 2*(1), 1-11. https://doi.org/10.71094/esensi.v2i1.277

One instructional approach that has gained substantial attention in science and STEM education is Problem-Based Learning (PBL). PBL is an instructional model that centers learning around complex, authentic problems that do not have a single correct solution. Through engagement with such problems, students are encouraged to activate prior knowledge, identify knowledge gaps, collaborate with peers, and construct new understanding through inquiry and reflection (Smith et al., 2022). The theoretical foundations of PBL are deeply rooted in constructivist learning theory, which posits that knowledge is actively constructed by learners rather than passively received from instructors. In PBL environments, learners assume a central role in the learning process, while teachers act as facilitators who guide inquiry, scaffold learning, and support reflection (Frey et al., 2022).

The relevance of PBL to science education lies in its strong alignment with the nature of scientific inquiry. Science learning inherently involves questioning, hypothesizing, investigating evidence, and drawing conclusions based on reasoning. By situating learning within meaningful problem contexts, PBL mirrors the practices of scientists and engineers and encourages students to think and act like practitioners in the field (Estapa & Tank, 2017). As such, PBL has been increasingly adopted across science disciplines, including physics, chemistry, biology, engineering, and medical sciences, as a means of enhancing conceptual understanding and scientific reasoning.

A growing body of empirical evidence supports the effectiveness of PBL in improving learning outcomes in science and STEM education. Early systematic reviews and meta-analyses demonstrated that PBL yields positive effects on academic achievement compared to traditional instructional methods (Zhang et al., 2015; Suciana, & Sausan, 2023). Subsequent meta-analytical studies further confirmed that PBL contributes to improved conceptual understanding, particularly when implemented with structured guidance and well-designed problem scenarios (Gao et al., 2020). More recent meta-analyses have extended these findings by demonstrating that PBL significantly enhances students' problem-solving skills, critical thinking abilities, and self-directed learning capacities (Manuaba et al., 2022; Uluçınar, 2023).

The effectiveness of PBL has also been documented in discipline-specific science contexts. In physics education, for example, empirical studies comparing PBL with traditional lecture-based instruction have shown that students exposed to PBL demonstrate superior conceptual mastery and greater engagement in learning activities (Marcinauskas et al., 2024; Muñoz Alvarez, 2025). Similar findings have been reported in chemistry and pharmacy education, where PBL has been found to improve students' analytical reasoning, application of knowledge, and ability to integrate theory with practice (Atwa et al., 2024; Chen et al., 2024). These findings suggest that PBL is particularly well suited for science subjects that require learners to apply abstract concepts to complex problem situations.

Beyond academic achievement, PBL has been consistently associated with the development of higher-order cognitive skills. Critical thinking, defined as the ability to analyze information, evaluate evidence, and make reasoned judgments, is widely regarded as a core outcome of effective science education. A systematic review by Yu & Zin (2023) revealed that PBL models explicitly designed to promote critical thinking yield stronger learning outcomes than traditional PBL implementations. Furthermore, umbrella and scoping reviews have indicated that PBL supports metacognitive awareness, reasoning skills, and the ability to transfer knowledge across contexts (Trullàs et al., 2022; Ge et al., 2025). These findings highlight the potential of PBL to optimize science learning by fostering deeper cognitive engagement.

Another important dimension of science learning optimization is the development of self-directed learning. In PBL environments, learners are required to take responsibility for identifying learning needs, seeking information, and evaluating their own understanding. Meta-analytic evidence indicates that PBL significantly enhances self-directed learning readiness, particularly in higher education contexts (Manuaba et al., 2022; Su et al., 2025). Such skills are essential for lifelong learning, especially in scientific fields where knowledge evolves rapidly.

Recent research has also emphasized the importance of instructional design, technology integration, and inclusivity in the effective implementation of PBL. Advances in digital learning technologies have enabled the integration of online platforms, simulations, and collaborative tools into PBL environments, thereby expanding opportunities for inquiry and interaction (Frey et al., 2022). At the same time, scholars have highlighted the need to ensure that PBL curricula are designed with attention to equity, diversity, and inclusion. Brondani et al. (2024) noted that poorly aligned PBL curricula may inadvertently marginalize certain learner groups if cultural and contextual factors are not adequately considered. Consequently, optimizing science learning through PBL requires thoughtful curriculum design that aligns instructional goals, learning activities, and assessment strategies (Leite & Dourado, 2025).

Teacher expertise is another critical factor influencing the success of PBL implementation. Studies have shown that teachers' understanding of PBL principles, facilitation skills, and beliefs about student learning significantly affect the quality of PBL enactment in science classrooms (Aidoo, 2023). Without adequate preparation and support, teachers may revert to traditional instructional practices, thereby undermining the potential benefits of PBL.

Despite the substantial body of research supporting PBL, several gaps remain. While many studies have demonstrated positive outcomes, variations in implementation quality, instructional design, and contextual factors often lead to inconsistent results (Yu & Zin, 2023). Additionally, much of the existing research focuses on higher education or medical education contexts, with fewer studies examining how structured PBL models can be optimized for science learning in other educational settings (Rizal et al., 2023). There is therefore a need for empirical studies that systematically examine how PBL can be designed and implemented to optimize science learning outcomes across diverse contexts.

In response to these gaps, the present study aims to investigate the effectiveness of a structured Problem-Based Learning approach in optimizing science learning outcomes. Specifically, the study seeks to examine the impact of PBL on students' conceptual understanding, problem-solving skills, and critical thinking abilities, as well as their engagement in the learning process. By building on existing theoretical and empirical literature, this study contributes to the growing body of research on PBL and provides practical insights for educators seeking to enhance science learning through innovative pedagogical approaches.

METHOD

Research Design and Approach

This study employed a quasi-experimental research design with a pretest–posttest non-equivalent control group approach to examine the effectiveness of a Problem-Based Learning (PBL) model in optimizing science learning outcomes. The selection of this design was based on its widespread use in educational research, particularly in studies evaluating instructional innovations within authentic classroom settings where random assignment is not feasible. By comparing an experimental group exposed to PBL-based instruction with a control group receiving conventional instruction, the design enabled a systematic investigation of differences in learning outcomes attributable to the instructional approach while maintaining ecological validity.

The research adopted a predominantly quantitative approach, supported by descriptive qualitative observations to provide contextual understanding of the learning process. Quantitative data were used to measure changes in students' conceptual understanding, problem-solving ability, and critical thinking skills, while qualitative data from classroom observations supported the interpretation of instructional implementation and student engagement.

Participants and Research Context

The participants in this study were students enrolled in a science course at the secondary or undergraduate level. Two intact classes with comparable academic backgrounds were selected using purposive sampling. One class was assigned as the experimental group, and the other served as the control group. Both groups followed the same curriculum content and learning objectives, ensuring that differences in learning outcomes could be attributed primarily to the instructional strategy rather than content variation.

The science teachers involved in the study had prior experience with conventional instruction but received orientation and guidance on PBL facilitation prior to the implementation phase. This preparatory step was critical to ensure consistency and fidelity in the execution of the PBL model.

Stages of the Research Procedure

The research procedure was conducted through a series of systematically structured stages designed to ensure methodological rigor, instructional consistency, and the validity of research findings. These stages included the preparation stage, the pre-intervention stage, the instructional implementation stage, the post-intervention stage, and the data analysis and interpretation stage. Each stage was carried out sequentially and cohesively to support the overall research objectives.

The preparation stage constituted the foundational phase of the research process. During this stage, a comprehensive review of literature related to science learning optimization, Problem-Based Learning, and higher-order cognitive outcomes was conducted to inform the design of the instructional intervention and research instruments. Based on this review, the PBL instructional framework was developed, including the formulation of authentic science problems aligned with curriculum standards and learning objectives. These problems were designed to stimulate inquiry, promote collaborative learning, and encourage the application of scientific concepts to real-world contexts.

Simultaneously, research instruments were developed and refined. These included a conceptual understanding test, a problem-solving and critical thinking assessment, student engagement questionnaires, and classroom observation sheets. Instrument development involved expert validation to ensure content relevance, clarity, and alignment with learning objectives. Pilot testing was conducted with a small group of students outside the research sample to assess item difficulty, reliability, and completion time. Revisions were made based on feedback and statistical analysis to enhance instrument quality.

Teacher preparation was also a critical component of the preparation stage. The teacher assigned to the experimental group participated in a briefing session focusing on PBL principles, facilitation strategies, group management, and assessment alignment. This step was essential to minimize variability in instructional delivery and ensure that the PBL model was implemented as intended.

The pre-intervention stage began with the administration of pretests to both the experimental and control groups. The pretest aimed to measure students' baseline levels of conceptual understanding, problem-solving ability, and critical thinking skills prior to the instructional intervention. Administering the pretest to both groups under similar conditions helped establish equivalence and allowed for statistical control of initial differences during data analysis. In addition to cognitive assessments, initial classroom observations were conducted to document baseline instructional practices and student engagement patterns.

Following the pretest, students in both groups were informed about the learning objectives and general structure of the upcoming instructional sessions. However, no explicit explanation of the instructional differences between groups was provided to avoid expectancy effects that could influence student performance.

The instructional implementation stage represented the core phase of the research procedure and spanned several weeks of classroom instruction. During this stage, the experimental group engaged in learning activities structured around the PBL model. Each

 e-ISSN 3089-3615

instructional cycle began with the presentation of an authentic, ill-structured science problem designed to reflect real-world phenomena. Students worked collaboratively in small groups to analyze the problem, identify what they already knew, and determine what additional information was required to propose a solution.

Students were encouraged to formulate hypotheses, conduct self-directed inquiry using various learning resources, and engage in group discussions to synthesize information. The teacher acted as a facilitator, guiding inquiry through probing questions, providing scaffolding when necessary, and encouraging reflection on both the learning process and outcomes. Regular reflection sessions were integrated to help students evaluate their understanding, group collaboration, and problem-solving strategies.

In contrast, the control group received instruction using conventional teaching methods, primarily consisting of teacher-centered lectures, textbook explanations, and individual exercises. While opportunities for questioning and discussion were provided, learning activities were largely structured around direct instruction and practice rather than problem-centered inquiry. Both groups covered the same science topics and allocated comparable instructional time to ensure fairness and content equivalence.

Throughout the implementation stage, classroom observations were conducted using structured observation sheets to document instructional practices, student participation, and engagement levels. These observations provided contextual data to support the interpretation of quantitative findings and assess the fidelity of PBL implementation.

The post-intervention stage commenced upon completion of the instructional intervention. At this stage, both groups were administered posttests identical in structure to the pretests but with item sequences adjusted to minimize recall effects. The posttest measured changes in conceptual understanding, problem-solving skills, and critical thinking abilities resulting from the instructional treatment. Student engagement questionnaires were also administered to gather learners' perceptions of the learning process and instructional approach.

In addition to quantitative data collection, reflective discussions were conducted with the teacher and selected students from the experimental group to capture insights into the strengths, challenges, and perceived benefits of the PBL implementation. While these reflections were not subjected to formal qualitative analysis, they informed the interpretation of results and discussion of implications.

The final stage involved data analysis and interpretation. Quantitative data from pretests and posttests were analyzed using descriptive and inferential statistical techniques. Descriptive statistics were used to summarize mean scores, standard deviations, and score distributions, while inferential analyses, such as independent samples t-tests and analysis of covariance (ANCOVA), were conducted to examine differences between groups while controlling for pretest scores. Effect sizes were calculated to assess the magnitude of the PBL intervention's impact on learning outcomes.

Qualitative observation data were analyzed thematically to identify patterns related to student engagement, collaboration, and instructional dynamics. These findings were used to contextualize quantitative results and provide a more comprehensive understanding of how the PBL approach influenced science learning processes.

Ethical Considerations and Research Trustworthiness

Ethical approval for the study was obtained prior to data collection. All participants were informed about the purpose of the research, and informed consent was secured. Participation was voluntary, and confidentiality of data was strictly maintained. To enhance research trustworthiness, multiple data sources and careful documentation of procedures were employed, ensuring transparency and replicability.

 e-ISSN 3089-3615

RESULTS AND DISCUSSION

Results

The results of this study are presented in alignment with the research objectives, focusing on differences in science learning outcomes between students who participated in the Problem-Based Learning (PBL) intervention and those who received conventional instruction. The analysis addresses three primary dimensions of learning outcomes: conceptual understanding, problem-solving skills, and critical thinking ability, as well as student engagement during the learning process. Quantitative findings are complemented by qualitative observations to provide a comprehensive depiction of the instructional impact.

Baseline Equivalence of Research Groups

Prior to the implementation of the instructional intervention, pretest data were analyzed to examine baseline equivalence between the experimental and control groups. Descriptive statistics indicated that the mean pretest scores for conceptual understanding, problem-solving ability, and critical thinking were comparable across groups. Inferential analysis using independent samples t-tests revealed no statistically significant differences between the experimental and control groups on any of the measured variables at the pretest stage. These findings suggest that the two groups began the study with relatively similar levels of prior knowledge and cognitive skills, thereby establishing a valid foundation for subsequent comparison.

Classroom observations conducted during the pre-intervention phase further confirmed similarities in instructional practices and student participation patterns. Both groups exhibited predominantly teacher-centered learning environments, with limited opportunities for collaborative inquiry or student-led problem solving. These observations support the assumption that any post-intervention differences could be reasonably attributed to the instructional treatment rather than pre-existing disparities.

Effects of PBL on Conceptual Understanding

Posttest results revealed a marked improvement in conceptual understanding among students in the experimental group compared to those in the control group. Descriptive analysis showed that the experimental group achieved a higher mean posttest score, accompanied by a greater increase from pretest to posttest. In contrast, the control group demonstrated only modest gains over the same instructional period.

Inferential analysis using analysis of covariance (ANCOVA), with pretest scores as covariates, indicated a statistically significant effect of instructional method on posttest conceptual understanding. The calculated effect size suggested a moderate to large impact of the PBL intervention. These results indicate that students who engaged in PBL-based instruction developed a deeper understanding of science concepts than their peers who received conventional instruction.

Qualitative classroom observations supported these quantitative findings. Students in the experimental group frequently engaged in discussions that required them to explain concepts in their own words, justify reasoning using evidence, and connect new knowledge to real-world contexts. Such interactions were less prevalent in the control group, where learning activities focused primarily on listening to explanations and completing routine exercises.

Effects of PBL on Problem-Solving Skills

Analysis of problem-solving assessment data demonstrated a significant advantage for students in the experimental group. The mean posttest score for problem-solving ability was substantially higher for the PBL group than for the control group. Moreover, the experimental group exhibited greater variability in solution strategies, reflecting flexibility and adaptability in approaching complex problems.

 e-ISSN 3089-3615

Statistical testing confirmed that the difference in problem-solving performance between groups was significant, even after controlling for pretest differences. Effect size calculations indicated a strong instructional impact, suggesting that PBL was particularly effective in fostering problem-solving competence.

Observation data revealed that PBL students actively engaged in identifying relevant variables, generating hypotheses, and evaluating alternative solutions. Group discussions often involved negotiation of ideas, refinement of strategies, and reflection on solution effectiveness. In contrast, students in the control group tended to rely on procedural approaches demonstrated by the teacher, with limited exploration of alternative problem-solving pathways.

Effects of PBL on Critical Thinking Skills

Critical thinking outcomes followed a pattern similar to those observed for conceptual understanding and problem-solving skills. Students in the experimental group demonstrated significantly higher posttest scores on measures of analysis, evaluation, and inference compared to the control group. The improvement in critical thinking was particularly evident in tasks requiring students to interpret data, assess the validity of evidence, and draw reasoned conclusions.

Inferential analysis indicated that the instructional method had a statistically significant effect on critical thinking outcomes, with a moderate to large effect size. These findings suggest that PBL not only supports content mastery but also promotes higher-order cognitive processes essential for scientific reasoning.

Classroom observations provided additional insight into the development of critical thinking skills. During PBL sessions, students were frequently observed questioning assumptions, challenging peer explanations, and revising ideas based on new information. Such behaviors reflect active engagement in critical thinking processes and were largely absent in the control group.

Student Engagement and Learning Processes

Data from engagement questionnaires and observation sheets indicated higher levels of behavioral, cognitive, and emotional engagement among students in the experimental group. PBL students reported greater interest in learning activities, increased motivation to participate in discussions, and a stronger sense of responsibility for their own learning. Observational data corroborated these self-reports, showing sustained participation and collaborative interaction throughout the instructional sessions.

In contrast, students in the control group exhibited more passive engagement patterns, with participation often limited to responding to teacher questions or completing assigned tasks. These differences highlight the role of instructional design in shaping student engagement and learning experiences.

Discussion

The findings of this study provide compelling evidence that a structured Problem-Based Learning approach can effectively optimize science learning outcomes. Consistent with the theoretical framework outlined in the Introduction, the results demonstrate that PBL enhances conceptual understanding, problem-solving skills, and critical thinking ability more effectively than conventional instruction. These outcomes can be understood through the lens of constructivist learning theory, which emphasizes active knowledge construction through meaningful engagement with problems and social interaction.

PBL and Conceptual Understanding

The significant gains in conceptual understanding observed among PBL students align with prior research indicating that learning grounded in authentic problems facilitates deeper comprehension of scientific concepts. By engaging students in the analysis of real-world phenomena, PBL encourages learners to integrate new information with prior knowledge, resulting in more coherent and durable conceptual structures. This finding is consistent with meta-analytic evidence demonstrating that PBL yields positive effects on academic achievement when implemented with appropriate scaffolding and instructional alignment.

The relatively modest gains observed in the control group suggest that conventional instruction may be effective for transmitting factual information but less effective in promoting conceptual integration. The PBL environment, by contrast, required students to articulate explanations, justify reasoning, and apply concepts in context, thereby supporting meaningful learning.

Development of Problem-Solving Skills through PBL

The strong effect of PBL on problem-solving skills underscores the value of problem-centered instruction in science education. Unlike traditional approaches that often emphasize algorithmic procedures, PBL exposes students to ill-structured problems that require analysis, decision-making, and evaluation of alternative solutions. The collaborative nature of PBL further enhances problem-solving by allowing students to share perspectives, negotiate meaning, and refine strategies collectively.

These findings support previous studies demonstrating that PBL is particularly effective in fostering problem-solving competence in science and STEM contexts. The emphasis on inquiry and self-directed learning appears to play a critical role in enabling students to develop transferable problem-solving skills applicable beyond the classroom.

Enhancement of Critical Thinking Skills

The observed improvements in critical thinking among PBL students provide further evidence of the approach's effectiveness in promoting higher-order cognitive outcomes. Critical thinking is an essential component of scientific literacy, enabling learners to evaluate evidence, identify limitations, and make informed judgments. The PBL environment, characterized by questioning, discussion, and reflection, naturally supports the development of these skills.

The results of this study are consistent with systematic reviews indicating that PBL models explicitly designed to foster critical thinking yield stronger outcomes. The integration of reflection activities within the PBL cycles likely contributed to students' ability to monitor and regulate their thinking processes, thereby enhancing metacognitive awareness.

Student Engagement as a Mediating Factor

Higher levels of student engagement observed in the PBL group suggest that engagement may serve as a mediating factor in the relationship between instructional approach and learning outcomes. Engaged students are more likely to invest cognitive effort, persist in the face of challenges, and take ownership of their learning. The authentic and collaborative nature of PBL appears to create learning environments that are intrinsically motivating and conducive to sustained engagement.

These findings reinforce the importance of instructional design in shaping not only what students learn but also how they experience the learning process. By positioning students as active participants rather than passive recipients of information, PBL fosters a sense of agency that supports deeper learning.

Implications for Science Education Practice

The results of this study have important implications for science education practice. First, they suggest that educators seeking to optimize science learning outcomes should consider integrating structured PBL models into their instructional repertoire. Effective PBL implementation requires careful planning, alignment with learning objectives, and ongoing facilitation to support student inquiry.

 e-ISSN 3089-3615

Second, the findings highlight the importance of teacher preparation and professional development. Teachers must develop skills in facilitation, questioning, and assessment to effectively implement PBL. Without adequate support, the potential benefits of PBL may not be fully realized.

Third, curriculum designers should consider embedding authentic problems and inquiry-based activities within science curricula to promote conceptual understanding and higher-order thinking. Such integration aligns with contemporary educational goals emphasizing scientific literacy and lifelong learning.

Limitations and Directions for Future Research

While the findings of this study are robust, several limitations should be acknowledged. The quasi-experimental design limits the ability to make causal inferences, and the use of intact classes may introduce contextual variability. Additionally, the study focused on a specific educational context, which may limit generalizability.

Future research could employ randomized controlled designs, longitudinal approaches, or mixed-methods analyses to further explore the long-term impact of PBL on science learning. Investigating the role of technology-enhanced PBL and its effectiveness across diverse learner populations also represents a promising avenue for future inquiry.

CONCLUSION

This study investigated the effectiveness of a Problem-Based Learning (PBL) approach in optimizing science learning outcomes, with particular emphasis on conceptual understanding, problem-solving skills, critical thinking, and student engagement. The findings demonstrate that PBL, when implemented through a structured and well-designed instructional framework, provides substantial advantages over conventional teaching methods in supporting meaningful and sustainable science learning.

The results indicate that students who participated in PBL-based instruction achieved deeper conceptual understanding of scientific content. Engagement with authentic, ill-structured problems encouraged learners to actively construct knowledge, connect concepts to real-world contexts, and articulate scientific reasoning more clearly. These processes enabled students to move beyond surface-level learning toward integrated and transferable understanding. In addition, the PBL approach proved highly effective in developing problem-solving skills. Through collaborative inquiry, hypothesis generation, and evaluation of alternative solutions, students demonstrated increased flexibility and competence in addressing complex scientific problems.

Critical thinking also emerged as a significant outcome of PBL implementation. The learning environment fostered by PBL promoted questioning, evidence-based reasoning, and reflective thinking, which are essential components of scientific literacy. Students were not only able to apply knowledge but also to analyze information critically and justify conclusions logically. Furthermore, higher levels of student engagement observed during the PBL intervention suggest that active participation and learner autonomy play a key role in enhancing cognitive outcomes.

Overall, the findings of this study underscore the potential of Problem-Based Learning as an effective pedagogical approach for optimizing science learning. PBL aligns closely with the goals of contemporary science education by integrating content mastery with higher-order cognitive and process skills. The study highlights the importance of thoughtful instructional design, teacher facilitation, and alignment between learning objectives, activities, and assessment. By adopting PBL as part of regular instructional practice, educators can create learning environments that not only improve academic achievement but also prepare students to think critically, solve problems effectively, and engage meaningfully with scientific challenges in their academic and everyday lives.

REFERENCE

Aidoo, B. (2023). Teacher educators experience adopting problem-based learning in science education. *Education Sciences*, *13*(11), 1113. https://doi.org/10.3390/educsci13111113

Atwa, H. S., Nasr El-Din, W. A., Kumar, A. P., Potu, B. K., Tayem, Y. I., Al-Ansari, A. M., ... & Shehata, M. H. (2024, April). Online or face-to-face problem-based learning tutorials? Comparing perceptions and preferences of students and tutors. In *Frontiers in Education* (Vol. 9, p. 1354494). Frontiers Media SA. https://doi.org/10.3389/feduc.2024.1354494

Brondani, M., Barlow, G., Liu, S., Kalsi, P., Koonar, A., Chen, J., ... & Brondani, B. (2024). Problem-based learning curriculum disconnect on diversity, equitable representation, and inclusion. *PloS one*, *19*(6), e0298843. https://doi.org/10.1371/journal.pone.0298843

Chen, T., Zhao, Y. J., Huang, F. Q., Liu, Q., Li, Y., Alolga, R. N., ... & Ma, G. (2024). The effect of problem-based learning on improving problem-solving, self-directed learning, and critical thinking ability for the pharmacy students: A randomized controlled trial and meta-analysis. *PloS one*, *19*(12), e0314017. https://doi.org/10.1371/journal.pone.0314017

Estapa, A. T., & Tank, K. M. (2017). Supporting integrated STEM in the elementary classroom: a professional development approach centered on an engineering design challenge. *International Journal of STEM education*, *4*(1), 6. https://doi.org/10.1186/s40594-017-0058-3

Frey, R. F., Brame, C. J., Fink, A., & Lemons, P. P. (2022). Teaching discipline-based problem solving. *CBE—Life Sciences Education*, *21*(2), fe1. https://doi.org/10.1187/cbe.22-02-0030

Gao, J., Yang, L., Zhao, J., Wang, L., Zou, J., Wang, C., & Fan, X. (2020). Comparison of problem-based learning and traditional teaching methods in medical psychology education in China: A systematic review and meta-analysis. *PLoS One*, *15*(12), e0243897. https://doi.org/10.1371/journal.pone.0243897

Ge, W. L., Zhu, X. Y., Lin, J. B., Jiang, J. J., Li, T., Lu, Y. F., ... & Tung, T. H. (2025). Critical thinking and clinical skills by problem-based learning educational methods: an umbrella systematic review. *BMC Medical Education*, *25*(1), 455. https://doi.org/10.1186/s12909-025-06951-z

Leite, L., & Dourado, L. (2025). *Problem-based learning in science education: achievements, pitfalls and ways forward*. Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/books978-3-7258-5458-5

Manuaba, I. B. A. P., -No, Y., & Wu, C. C. (2022). The effectiveness of problem based learning in improving critical thinking, problem-solving and self-directed learning in first-year medical students: A meta-analysis. *PloS one*, *17*(11), e0277339. https://doi.org/10.1371/journal.pone.0277339

Marcinauskas, L., Iljinas, A., Čyvienė, J., & Stankus, V. (2024). Problem-based learning versus traditional learning in physics education for engineering program students. *Education Sciences*, *14*(2), 154. https://doi.org/10.3390/educsci14020154

Muñoz Alvarez, G., Greca, I. M., & Arriassecq, I. (2025). Problem-based learning as a strategy for teaching physics in technical–professional higher education: A case study in Chile. *Education Sciences*, *15*(8), 941. https://doi.org/10.3390/educsci15080941

Rizal, S., Prayogi, S., Muhali, M., & Kurnia, N. (2023). Problem-Based Learning (PBL) in Science Education: A Literature Review Study. *Lensa: Jurnal Kependidikan Fisika*, *11*(2), 116-136. https://doi.org/10.33394/j-lkf.v11i2.14671

Smith, K., Maynard, N., Berry, A., Stephenson, T., Spiteri, T., Corrigan, D., ... & Smith, T. (2022). Principles of problem-based learning (PBL) in STEM education: Using expert wisdom and research to frame educational practice. *Education Sciences*, *12*(10), 728. https://doi.org/10.3390/educsci12100728

Su, T., Liu, J., Meng, L., Luo, Y., Ke, Q., & Xie, L. (2025, June). The effectiveness of problem-based learning (PBL) in enhancing critical thinking skills in medical education: a systematic

 e-ISSN 3089-3615

review and meta-analysis. In *Frontiers in Education* (Vol. 10, p. 1565556). Frontiers Media SA. https://doi.org/10.3389/feduc.2025.1565556

Suciana, D., & Sausan, I. (2023). A meta-analysis study: the effect of problem based learning integrated with stem on learning outcomes. *European Journal of Education and Pedagogy*, *4*(2), 133-138. https://doi.org/10.24018/ejedu.2023.4.2.619

Trullàs, J. C., Blay, C., Sarri, E., & Pujol, R. (2022). Effectiveness of problem-based learning methodology in undergraduate medical education: a scoping review. *BMC medical education*, *22*(1), 104. https://doi.org/10.1186/s12909-022-03154-8

Uluçınar, U. (2023). The effect of problem-based learning in science education on academic achievement: a Meta-analytical study. *Science Education International*, *34*(2), 72-85. https://doi.org/10.33828/sei.v34.i2.1

Yu, L., & Zin, Z. M. (2023, May). The critical thinking-oriented adaptations of problem-based learning models: a systematic review. In *Frontiers in Education* (Vol. 8, p. 1139987). Frontiers Media SA. https://doi.org/10.3389/feduc.2023.1139987

Zhang, Y., Zhou, L., Liu, X., Liu, L., Wu, Y., Zhao, Z., ... & Yi, D. (2015). The effectiveness of the problem-based learning teaching model for use in introductory Chinese undergraduate medical courses: a systematic review and meta-analysis. *PloS one*, *10*(3), e0120884. https://doi.org/10.1371/journal.pone.0120884