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The effect of problem-based learning on higher-order thinking skills in sustainable development goal-oriented learning

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ABSTRACT

Higher-order thinking skills (HOTS) are crucial for tackling the demands of the 21st century and are closely connected with sustainable development goal (SDG) 4, SDG 8, and SDG 9. Their development supports quality education, employability, and innovation. Thus, HOTS play a strategic role in achieving the 2030 sustainable development agenda. This research investigates how problem-based learning (PBL) can effectively improve university students' HOTS. The study adopted a quasi-experimental approach using a pretest-posttest comparison group, consisting of 100 sixth-semester students from three different universities. The stimulus group received PBL-based instruction, while the comparison group was taught using direct instruction (DI). The data were analyzed using normality checks, variance homogeneity assessments, and independent samples t-tests. The results showed that the PBL group's posttest scores (M=20.16; SD=1.608) were markedly higher than those of the control group (M=17.14; SD=1.948), yielding a t-statistic of 8.453 with a significance level of p=0.000 (p<0.05). The findings offer compelling evidence that PBL substantially improves students' critical thinking skills. The findings suggest that PBL is an effective pedagogical approach for fostering HOTS and aligns with the objectives of sustainable education, promoting active, reflective, and analytical learning.

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1. INTRODUCTION

The development of learning oriented towards higher-order thinking skills (HOTS) is one of the initiatives of the Ministry of Education and Culture, through the directorate general of teachers and education personnel, to improve the quality of the learning process and the quality of graduates [1]. HOTS are regarded as vital in higher education, as they involve critical, analytical, and creative reasoning required to address today's complex global issues. An instructional strategy widely recognized for cultivating HOTS is problem-based learning (PBL). This approach not only immerses students in addressing real-world problems but also enhances their critical thinking, mathematical creativity, and creative dispositions across various educational settings [2]–[4]. Furthermore, PBL nurtures collaboration, interdisciplinary problem-solving, and transferable skills, while aligning with the United Nations sustainable development goal (SDG) 4 (quality education) by preparing learners to contribute to inclusive, innovative, and sustainable growth.

The integration of PBL with the SDGs underscores its transformative potential in higher education. PBL equips students not only with theoretical knowledge but also with problem-solving abilities,

collaboration, and adaptability, which are essential for achieving SDG 4 (quality education). Moreover, by fostering critical thinking and reflective practice, PBL enhances learners' readiness for SDG 8 (decent work and economic growth), enabling them to enter the workforce with advanced skills and adaptability. It also strengthens SDG 9 (industry, innovation, and infrastructure) by cultivating creativity and innovation in tackling real-world issues. Thus, embedding PBL within the curriculum reflects a global educational commitment to shaping critical, innovative, and future-oriented graduates who can meaningfully contribute to the realization of the 2030 SDGs [5], [6].

The integration of SDGs into mathematics learning through a PBL approach is achieved by presenting real problems related to environmental, social, and economic issues. Through the process of investigation and problem-solving, students utilize mathematical concepts to analyze data, evaluate alternative solutions, and make evidence-based decisions [7]–[9]. Active involvement in contextual learning has been proven to improve critical thinking, problem-solving, and numeracy skills, while helping students understand the relevance of mathematics to sustainable development [10], [11].

The implementation of SDGs in mathematics learning can be realized through the analysis of sustainability data in statistics, calculus, and applied mathematics courses, such as data on environmental pollution, energy consumption, poverty, or educational inequality. Through mathematical modeling and data interpretation activities, students are trained to develop solutions to various sustainability challenges, including resource management, energy efficiency, and socio-economic planning [12], [13]. These activities not only strengthen the mastery of mathematical concepts and mathematical modeling skills, but also improve data literacy, high-level thinking skills, collaboration, and social awareness of students on sustainable development issues [14]–[16].

PBL is a learning approach that uses authentic problems as the primary driver of the learning process, encouraging students to engage in active, structured inquiry. PBL serves not only as a pedagogical strategy but also as a means of developing HOTS through complex, context-based problem-solving activities. Various studies have shown that PBL can improve students' analytical and evaluative abilities through engagement in authentic scientific investigations [17], [18]. In this process, students formulate questions, gather information, test hypotheses, and evaluate solutions, while simultaneously developing metacognitive skills to plan, monitor, and evaluate their own thinking. These metacognitive abilities are important factors supporting the effectiveness of problem-solving and the quality of learning [19].

Furthermore, cognitive engagement arises from the active interaction among PBL, inquiry, and metacognition. This engagement reflects the depth of students' thinking processes in understanding concepts, integrating new knowledge, and applying it to complex situations. High levels of cognitive engagement are positively correlated with increased HOTS, particularly in the analysis, evaluation, and creation aspects. Therefore, PBL can be positioned as a pedagogical framework that integrates inquiry and metacognition to foster deep cognitive engagement, ultimately contributing significantly to students' HOTS development [20], [21]. To provide a more comprehensive theoretical representation of the relationships between these constructs, the conceptual framework of this study is presented in Figure 1.

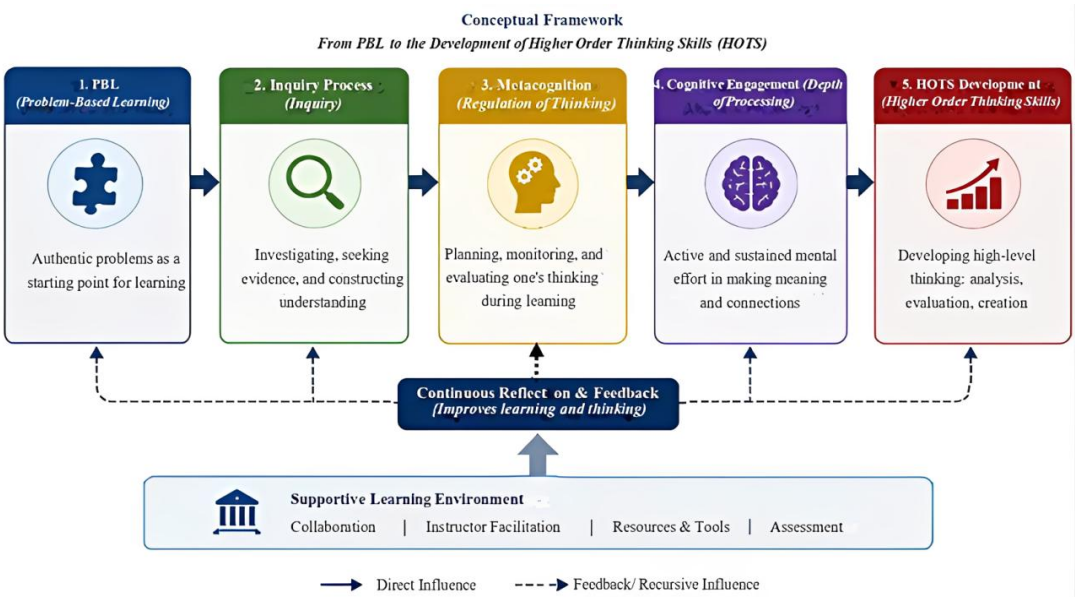


Figure 1. Conceptual framework for HOTS development through PBL

In this context, the development of HOTS has become a top priority in higher education, as students face increasingly complex academic, professional, and social challenges. Higher education plays a strategic role in shaping human resources who are critical and adaptive to the dynamics of the times. In the context of globalization, the fourth industrial revolution, and rapid developments in digital education, students are expected not only to acquire theoretical and factual knowledge but also to build HOTS, encompassing analysis, evaluation, creativity, and problem-solving abilities [22]–[24]. These competencies play a vital role in equipping learners to handle challenging situations in real-world contexts [25]. However, many students remain passive during learning, relying on memorization rather than being trained to analyze, evaluate, and solve problems independently. One contributing factor is the predominant use of direct instructional models, which are teacher-centered and insufficiently engage students in critical thinking.

One of the learning models considered effective in fostering HOTS is PBL [25]–[27]. PBL positions real-world problems as the initial trigger for the learning process, encouraging students to engage in analytical reasoning, problem-solving, and collaborative discussions. Through such active involvement, learners not only acquire conceptual understanding but also strengthen critical, creative, and cooperative thinking skills. Accordingly, PBL aligns with the core principles of 21st-century education, which emphasize the mastery of the 4Cs: critical thinking, creativity, collaboration, and communication [28]. In addition, PBL provides opportunities for learners to engage in independent, self-managed learning activities, where they take responsibility for identifying, analyzing, and resolving problems. Moreover, PBL has proven effective in boosting students' enthusiasm and participation by making the content more meaningful in relation to real-world experiences.

The effectiveness of PBL in enhancing students' HOTS is evident through its significant contribution to the development of critical thinking and problem-solving abilities across various educational contexts [29]–[32]. This approach frames learners as active partners in addressing authentic, real-world challenges. PBL requires them to think critically, seek practical solutions, and engage in systematic stages such as problem identification, information gathering, solution formulation, and result evaluation, which in turn foster skills in analyzing complex problems, stimulating creativity, and encouraging collaboration [33]–[36]. Furthermore, implementing the PBL module fosters the development of problem-solving skills by encouraging students to conduct direct investigations. At the same time, the emphasis on scientific thinking strengthens reasoning abilities in drawing conclusions and managing information at the secondary education level [37]–[39].

Empirical evidence from subsequent studies demonstrates that PBL-designed learning materials support improvements in students' problem-solving skills through activities that require direct investigation and problem-solving [37], [40], [41]. PBL also emphasizes the role of scientific thinking in fostering students' capacity to solve problems at the high school level [38], [42], [43]. Research results show that learners participating in PBL experience notable improvement in their reasoning skills, both in their ability to conclude and in their ability to manage related information.

PBL has been widely recognized as a powerful instructional model for developing HOTS, particularly in critical thinking and problem-solving. When PBL is combined with supportive learning media, students' analytical abilities in comprehending physics concepts are significantly strengthened [44]. Other studies have also shown through randomized controlled trials and meta-analyses that PBL has a substantial impact on improving pharmacy students' problem-solving skills, self-directed learning, and critical thinking capacity [45]. Active participation in PBL encourages learners to practice analysis, questioning, and critical evaluation of information, all of which are fundamental dimensions of both critical and creative thinking [40], [46].

PBL in higher education environments encourages effective collaboration and interaction, thereby improving students' problem-solving abilities and communication skills [36]. Through collaborative learning, students gain not only theoretical understanding but also the ability to apply it effectively in real-world contexts [47]–[49]. Hence, it is vital to investigate the effectiveness of PBL in strengthening learners' critical thinking and problem-solving competencies. Beyond cognitive outcomes, PBL contributes to the development of soft skills such as teamwork, adaptability, and self-regulation, which are indispensable in professional settings. This research endeavors to provide empirical evidence regarding the influence of PBL in higher education contexts

PBL does not merely focus on finding answers to a given problem but also emphasizes the thinking processes underlying problem-solving. Engagement in intensive dialogue encourages learners to analyze the fundamental causes of issues, construct hypotheses, and evaluate diverse possible solutions in light of their existing knowledge base [50]–[52]. The process enables learners to cultivate systematic, reflective, and analytical thinking, thereby reinforcing the continuous advancement of critical thinking competencies. As a result, PBL emerges as a suitable approach for promoting metacognitive awareness, namely, students' ability to recognize and regulate their cognitive activities when confronted with complex issues.

Furthermore, PBL emphasizes active student engagement in analyzing information, constructing arguments, and drawing logical conclusions from multiple perspectives [53], [54]. Such activities require students not merely to receive information passively but to transform it into new, more meaningful knowledge. The development of critical thinking is grounded in reasoning processes that encourage learners to appraise information validity, identify inherent biases, and establish logical relationships among interconnected concepts. Building on this premise, the study aims to evaluate the effectiveness of PBL in fostering students' critical thinking and to examine potential differences in HOTS, with an emphasis on critical thinking, between students engaged in PBL and their peers receiving direct instructional models.

Based on this background, there are two problem formulations in this research: first, is there a significant difference in HOTS between students taught using PBL and those taught using a direct learning model? Second, can the implementation of PBL significantly improve students' critical thinking skills? Meanwhile, this study hypothesizes that there is a significant difference in HOTS between students taught using the PBL model and those taught using the direct learning model. Second, the application of the PBL model can significantly improve students' critical thinking skills. As a basis for this research, various previous studies have examined the contribution of PBL to the development of HOTS.

Previous studies have shown that PBL is effective in improving HOTS. PBL is also considered capable of encouraging students to be more active in analyzing, evaluating, and solving problems through contextual learning. However, studies that specifically integrate HOTS indicators with the context of SDGs in mathematics learning in higher education are still relatively limited. Therefore, this study offers an advantage by more specifically examining the development of students' critical thinking skills based on HOTS indicators in mathematics learning oriented towards SDGs in the context of higher education.

2. METHOD

2.1. Research design

This study employed a quasi-experimental pretest–posttest comparison group design [53] to evaluate the impact of implementing the PBL approach on the development of students' HOTS. The research was conducted with two cohorts: an experimental group that received the PBL intervention and a comparison group instructed through the direct instruction (DI) model. Before the intervention, both groups completed a pretest to evaluate their baseline HOTS. Following the instructional treatments, a posttest was administered to both groups to examine subsequent changes in HOTS, with the difference in scores used to evaluate the effectiveness of PBL. This design was chosen because it allows for an examination of instructional interventions, despite the lack of full randomization in subject selection [54].

2.2. Research subjects

The subjects of this study were 100 sixth-semester mathematics education students from three universities: Wisnuwardhana University, Nusantara PGRI University of Kediri, and Madura University of Pamekasan. The details were 20 students from Universitas Wisnuwardhana of Malang, 40 students from Nusantara PGRI University of Kediri, and 40 students from Madura University of Pamekasan. The subjects were between 18 and 19 years old. The 100 subjects were divided into two groups: 50 as the experimental group and 50 as the control group. Participants were recruited through purposive sampling, a non-probability technique that applies predetermined criteria aligned with the objectives of the study, including active enrollment, prior exposure to PBL, and being willing to participate in the entire research process [55]. Purposive sampling is often used when specific characteristics are sought within a population, ensuring the sample aligns with the study's research objectives [56], [57].

The research group determination was carried out after the participant selection process was completed. Subjects were grouped based on pre-formed classes (intact groups) at each university. Next, the researchers, along with the lecturers, identified classes with relatively equivalent academic abilities, learning outcomes, and learning experiences. Based on this identification, one class was designated as the experimental group, receiving PBL-based instruction, while the other class was designated as the control group, receiving DI.

The distribution of subjects across universities was not proportionally balanced, but adjusted based on the number of students meeting the research criteria at each institution. To control potential cross-group contamination, the intervention was administered separately to each class and university, and the use of learning tools was limited to each group throughout the study. The learning intervention was conducted over two learning sessions. Each session lasted 150 minutes and covered the same material for both groups. Equivalence of learning instruction was maintained through the use of the same teaching materials, learning outcomes, time allocation, and evaluation tools for both groups, with the main difference being the learning model applied throughout the study.

2.3. Research instrument

The main instrument employed in this study was a HOTS assessment, developed to evaluate students' critical thinking competencies. The test was constructed with reference to the revised Bloom's taxonomy, focusing on higher-level cognitive processes, namely analysis, evaluation, and creation [58]. The HOTS test was administered as both a pretest and a posttest to measure the students' cognitive development after receiving treatment. This approach is consistent with the recommendation to use valid, structured assessments to measure higher cognitive skills [59], [60].

This assessment instrument is designed in the form of essay questions based on HOTS to measure students' HOTS in linear programming. The essay format was chosen because it can measure students' analytical, evaluation, and creative abilities more deeply through a contextual problem-solving process. The instrument consists of five questions arranged based on the revised Bloom's taxonomy, namely C4 (analysis), C5 (evaluation), and C6 (creation). Question C4 directs students to analyze demand comparisons and determine delivery proportions. Question C5 requires students to evaluate distribution strategies based on cost efficiency and capacity limitations. Meanwhile, question C6 measures students' ability to construct mathematical models and creatively design optimal solutions.

The assessment rubric in this instrument is designed to comprehensively assess students' achievement of HOTS. Aspects assessed include problem-analyzing skills, the accuracy of mathematical concepts, the ability to construct linear programming models, calculation accuracy, argumentation quality, and the ability to systematically present solutions. Each assessment indicator uses a graduated scale so that lecturers can objectively differentiate students' levels of mastery. The rubric is also designed to support authentic assessment by considering students' thinking processes and reasoning quality, not just the final answer.

The instrument used to measure students' HOTS consisted of five items. Before being used in the study, the instrument's validity was tested to ensure that each question accurately and precisely measured the intended ability. This test determined whether each item correlated with the total score and truly represented the construct being measured. The results of the instrument's validity test are presented in Table 1.

Table 1. The results of the research instrument validity test

Test item	Pearson correlation	Sig. (2-tailed)	Decision
1	0.278	0.005	Valid
2	0.361	0.000	Valid
3	0.211	0.035	Valid
4	0.465	0.000	Valid
5	0.463	0.000	Valid

The results of the validity test, as in Table 1, explained that all items showed adequate validity, with Pearson correlation coefficients ranging from 0.211 to 0.465 and significance values below 0.05 ($p<0.05$). This range of values was obtained from the lowest Pearson correlation value in item number 3 of 0.211 and the highest value in item number 4 of 0.465. These results indicate that each item has a positive relationship with the total instrument score at a low to moderate correlation level, so all items are declared valid and suitable for use in research because they can measure the same construct as the instrument as a whole.

Meanwhile, expert validation results indicated that the question instrument was suitable for use. The assessment results showed that the content suitability aspect received a score of 3 because the questions aligned with HOTS learning outcomes and were relevant to the linear programming material. However, some clarification was needed regarding optimization. The problem clarity aspect also received a score of 3 because the question context was deemed sufficiently clear and contextual. Furthermore, the question construction aspect received a score of 4 because the questions were systematically structured and able to encourage students' analytical, evaluation, and creative abilities.

For the cognitive-level suitability aspect, the validator gave a score of 4 because each question met the C4, C5, and C6 levels. The language aspect received a score of 3, with minor suggestions to make the sentences more concise and effective. Furthermore, the data completeness aspect received a score of 4 because the data presented was complete and supported the problem-solving process. The clarity of instructions and completion time aspects each received a score of 3 because there was still a need for additional sample answer formats and more explicit time estimates.

After the instrument's validity is confirmed, a reliability analysis is conducted to assess its internal consistency. This procedure aims to determine the extent to which the instrument produces stable, consistent results in measuring the construct under study. Instruments that meet the criteria for validity and reliability are considered capable of producing accurate and reliable data. The results of the reliability analysis are presented in Table 2.

Table 2. The results of the research instrument reliability test (reliability statistics)

Cronbach's alpha	Cronbach's alpha based on standardized items	N of items
0.722	0.726	5

Table 2 indicates that the reliability analysis showed satisfactory internal consistency (α=0.722). This Cronbach's alpha value is above the minimum threshold of 0.70, thus concluding that the instrument has a good level of reliability. It indicates that the items in the instrument have a fairly high level of internal consistency in measuring the same construct. Therefore, this research instrument can be considered reliable and suitable for use in data collection.

2.4. Data analysis technique

Data analysis involved several steps. The pretest and posttest results from both the experimental and comparison groups were systematically coded and organized. To verify the assumptions of parametric analysis, data normality was examined using the Shapiro–Wilk test, while homogeneity of variances was assessed through Levene's test to ensure that parametric tests could be applied [61]. Descriptive statistics (mean and standard deviation or SD) provided an overview of the data, and inferential analyses were carried out using independent and paired sample t-tests to determine whether the PBL model had a significant effect on HOTS improvement [62]. To assess the practical relevance of the results, effect size analysis using Cohen's measure was performed, accompanied by graphical representations to depict the data. These methods align with best practices in educational research for analyzing pretest-posttest data [54].

2.5. Research procedure

The research procedure in this experimental study began with a pre-test administered to both the experimental and control groups to determine their initial HOTS abilities before receiving the treatment. The pre-test was administered simultaneously to both groups using the same instrument to ensure objective and comparable data. Next, the experimental group was given the PBL model, while the control group continued using the direct learning model. After the learning process was completed, both groups were given a post-test using the same instrument to measure students' HOTS.

Data from the pre-test and post-test were then collected and analyzed to determine differences in results between the two groups, allowing conclusions to be drawn regarding the effectiveness of the treatment. Statistical analysis, including normality and homogeneity tests, was applied to the post-test data to ensure that the results truly reflected the effects of the learning treatment [63]. This entire process aimed to determine whether the PBL model was significantly more effective in improving HOTS than traditional learning methods, following standard procedures in quasi-experimental research [64].

3. RESULTS AND DISCUSSION

The results and discussion section presents the research findings obtained from the data analysis and a discussion linking these findings to theory and previous research findings. In this section, the collected data are systematically analyzed to answer the research problem formulation, then interpreted to explain the meaning of the results. Furthermore, the discussion also highlights the implications of the research findings, particularly regarding the effectiveness of the learning model implementation in improving students' HOTS.

As a first step in discussing the research results, descriptive statistics are presented to provide an overview of students' critical thinking skills in the two groups studied. This presentation aims to facilitate understanding of the data distribution before further analysis. Summary statistics of students' critical thinking performance in the stimulus group and the comparison group, reporting sample size (N), minimum and maximum scores, means, and SD, are presented in Table 3.

Table 3. Mean pretest scores of the stimulus and comparison groups

Groups	N	Min	Max	Mean	SD
Stimulus	50	10	15	12.10	1.359
Comparison	50	10	16	12.20	1.262

Table 3 presents descriptive statistics of students' critical thinking abilities at the pre-test stage for the stimulus group and the comparison group. Each group consisted of 50 participants (N=50), resulting in a total sample size of 100. Both groups obtained an identical minimum critical thinking score of 10. However, the maximum score in the stimulus group was 15, while the comparison group reached 16.

This indicates that the score distribution in the comparison group was slightly wider compared to the stimulus group. Students in the stimulus group reported an average score of 12.10 with a SD of 1.359, while those in the comparison group demonstrated a mean of 12.20 and a SD of 1.262. The negligible mean score gap of 0.10 points implies that students in both groups exhibited similar levels of critical thinking before the treatment. Pretest scores indicated comparable baseline critical thinking ability across groups.

In general, the descriptive statistics reveal no meaningful differences in critical thinking ability between the stimulus and comparison groups at the pretest stage. Such equivalence is crucial for maintaining internal validity, as any variations detected in the posttest outcomes can be attributed with greater confidence to the intervention rather than to initial group disparities. To further strengthen this conclusion, subsequent analyses such as the t-test and the test of homogeneity of variances (Levene's test) are necessary to examine whether the observed descriptive differences are statistically significant after the treatment was administered to each group. A post-test was conducted to measure changes in students' critical thinking skills following the learning intervention. The post-test results for each group can be seen in Table 4.

Table 4. Mean posttest scores of the stimulus and comparison groups

Groups	N	Minimum	Maximum	Mean	SD
Stimulus	50	16	23	20.16	1.608
Comparison valid N (listwise)	50	14	21	17.14	1.948

Table 4 presents descriptive statistics summarizing the critical thinking performance of students in the stimulus group and the comparison group after the intervention was given. Each group included an equal number of participants (N=50), allowing for a balanced analysis. For the experimental group, scores ranged from 16 to 23, with a mean of 20.16 and an SD of 1.608. In contrast, the comparison group recorded scores between 14 and 21, yielding a mean of 17.14 and a SD of 1.948.

The observed mean difference of 2.72 points between the stimulus and comparison groups demonstrates a notable improvement in the stimulus group relative to the comparison group. The higher average score in the stimulus group implies that the implemented treatment or intervention may have positively influenced students' critical thinking skills. Additionally, the broader span between the minimum and maximum scores in the stimulus group indicates generally stronger cognitive performance. In contrast, the comparison group's larger SD (1.948 versus 1.512) suggests greater variability in critical thinking outcomes, while the stimulus group showed more consistent performance across participants.

Overall, the results indicate that the intervention provided to the stimulus group may effectively enhance critical thinking skills. However, this inference requires validation through inferential statistical analyses, such as an independent t-test, to ascertain whether the observed differences in means between groups are statistically significant rather than due to random variation. Furthermore, additional assessments, including tests of normality and homogeneity of variance, are essential to confirm the robustness and reliability of the data before drawing definitive conclusions about the intervention's efficacy. These findings underscore the importance of rigorous statistical verification in evaluating educational interventions.

This finding suggests that the observed difference in mean posttest scores between the two groups is suitable for further examination using parametric statistical methods, as a key assumption for these analyses has been met. Conducting such tests will allow for a more precise determination of whether the intervention produced statistically significant effects. Once these assumptions are satisfied, the next step in the analysis is to conduct an inferential statistical test to examine the significance of differences between groups. Therefore, the results of the effect test using the independent samples test are presented to determine whether the observed differences are statistically significant.

Table 5 shows that the independent samples t-test conducted on the posttest scores indicated that Levene's test for equality of variances yielded $F=2.478$ with a significance value of 0.119 ($p>0.05$), suggesting that the variances between the two groups were equal. Consequently, the analysis was performed under the assumption of equal variances. The mean difference analysis produced a t-value of 8.453 with 98 degrees of freedom and a two-tailed significance of 0.000 ($p<0.05$), demonstrating a statistically significant difference between the posttest outcomes of the stimulus and comparison groups.

The mean difference of 3.020 indicates that the stimulus group achieved higher average posttest scores compared to the comparison group. Consistent with this observation, the independent samples t-test produced a significance value of 0.000 ($p<0.05$), confirming a statistically significant difference between the posttest means of the two groups. These results suggest that the implementation of the PBL model had a substantial impact on enhancing students' higher-order critical thinking skills, with participants in the PBL group outperforming those instructed through the DI model. To further substantiate the magnitude of these differences, effect size analyses were performed to determine the practical significance of the observed results.

Table 5. Results of the effect test using the independent samples test

		Independent samples test Levene's test for equality of variances		T-test for equality of means			
		F	Sig.	t	df	Sig. (2-tailed)	Mean difference
Post test scores	Equal variances assumed	2.478	0.119	8.453	98	0.000	3.020
	Equal variances not assumed			8.453	94.599	0.000	3.020

The results of the independent samples t-test showed that there was a significant difference between the experimental group and the control group ($t(98)=8.453$, $p<0.001$). This finding indicates that students who learned through the PBL model achieved HOTS achievements compared to students who followed conventional learning. In addition to statistical significance, the magnitude of the intervention effect was analyzed using Cohen's d effect size value and obtained a value of 1.69. Based on commonly used criteria, this value is included in the large effect category, which indicates that the effect of the application of PBL on HOTS is at a strong level. These results confirm that the effectiveness of the learning model is not only reflected in the differences between groups, but also in the magnitude of the impact produced on improving HOTS.

This difference occurred because, during the learning process, students participating in PBL demonstrate higher levels of cognitive engagement than those receiving DI. It is evident when students face contextual mathematical problems that require them to identify relevant information, discuss alternative strategies, and formulate solutions collaboratively. In PBL classes, students are more actively involved in asking questions, explaining ideas, and evaluating the validity of solutions during group discussions. These activities encourage students to process information more deeply than simply applying formulas procedurally. Furthermore, findings during classroom observations also indicate that PBL stimulates students' critical thinking because learning activities require continuous reasoning and reflection. When students encounter difficulties solving problems, they tend to reevaluate their understanding, compare various approaches, and justify their arguments with logical evidence. This reflective process rarely occurs in direct instructional classes, where learning activities largely focus on listening to explanations and following teacher directions.

During the learning process, students in the PBL group demonstrated higher levels of collaborative interaction than those in the direct learning group. This significantly contributed to the development of HOTS. Students frequently exchanged perspectives, challenged each other's reasoning, and negotiated solutions within their groups. These interactions created cognitive conflict, encouraging deeper conceptual understanding and critical evaluation of ideas. In contrast, students in the direct learning setting demonstrated relatively limited interaction because classroom activities were generally teacher-centered. Therefore, contextual findings during the implementation of the learning indicated that the effectiveness of PBL in promoting HOTS emerged from the active inquiry process, reflective thinking, and collaborative problem-solving activities embedded within the learning environment.

These results are consistent with prior studies indicating that the PBL approach more effectively promotes higher-order critical thinking skills than the DI model. Imamah *et al*. [65] reported that the proportion of HOTS in the stimulus class (90.62%) was markedly greater than that in the comparison class (40.63%). Similarly, Siew and Basari [66] found that the integration of PBL in mathematics instruction improved HOTS, encompassing fundamental competencies, including critical thinking and problem-solving for students' success in the 21st century [67]. The research demonstrated that PBL had a more pronounced effect on students' learning outcomes than DI. Additionally, subsequent studies have provided evidence that PBL, designed to enhance HOTS, effectively promotes critical, analytical, evaluative, and creative thinking across diverse educational contexts [45], [68], [69].

Leasa *et al*. [70] highlighted the pivotal role of teachers in fostering the development of higher-order critical thinking skills through inquiry-driven problem-solving activities in PBL. Their findings demonstrated that PBL not only substantially improved students' academic performance but also enhanced their effectiveness in communicating within group discussions. Additionally, Hidayati *et al*. [71] emphasized that PBL facilitates students' decision-making processes, reflecting the engagement of critical thinking skills that are fundamental for successful problem-solving.

The findings of Dolmans *et al*. [72] emphasize that PBL provides students with more meaningful learning experiences, as they are directly engaged in exploring knowledge through contextual problems. Such engagement has been shown to enhance their ability to analyze information, evaluate arguments, and draw logical conclusions. It is consistent with the study by Rodniam and Suksuwanont [73], which found that students accustomed to PBL exhibited higher levels of self-regulated learning. This factor directly supports the development of critical thinking skills. Hence, PBL is not merely a teaching method but a pedagogical strategy that develops students' HOTS.

Furthermore, Chen *et al*. [74] revealed that PBL enhances students' capacity to integrate knowledge across different disciplines, serving as a critical indicator of their critical thinking abilities. In mathematics education, learners participating in PBL exhibited a stronger aptitude for relating abstract concepts to real-world contexts. These findings are consistent with Cong and Ironsi [75], who reported that PBL fosters students' analytical skills by engaging them in authentic problem scenarios that encourage the exploration of multiple solution pathways. Consequently, PBL impacts not only cognitive learning outcomes but also the deeper internalization of knowledge.

The incorporation of technology into PBL has been observed to enhance students' critical thinking significantly [76]. The integration of digital tools within PBL facilitates simulations, data analysis, and online collaborative activities, thereby fostering more interactive and engaging learning environments. Similar findings have been reported in previous studies, which indicate that e-learning–enhanced PBL substantially improves both problem-solving and critical thinking skills compared to conventional instructional methods [49], [77]. These results suggest that PBL's effectiveness can be further strengthened by systematically integrating digital media into the learning process.

The positive impact of PBL on the development of critical thinking skills is supported by recent international studies. For instance, a meta-analysis in nurse educator reported that PBL significantly enhances critical thinking among nursing students, with a standardized mean difference (SMD) of 0.47 (95% CI=0.33–0.61; $p<0.01$) [51]. These results reinforce the notion that PBL is an effective instructional approach for fostering higher-order cognitive skills across diverse educational settings [78]. Consequently, this body of evidence reinforces the international empirical support for implementing PBL in higher education as a means to cultivate critical thinking skills.

Furthermore, evidence from various studies indicates that PBL surpasses conventional teaching methods in enhancing students' critical thinking skills. Recent meta-analytic research supports these conclusions, showing that PBL effectively promotes critical thinking, problem-solving abilities, and self-directed learning across a wide range of academic disciplines [76], [79]. Collectively, these studies indicate that PBL creates a learning environment that encourages students to actively analyze, evaluate, and synthesize information. Consequently, PBL implementation not only enhances overall learning outcomes but also promotes more reflective and collaborative approaches to learning [80].

The advantages of PBL are reflected in its capacity to promote student engagement, creativity, and autonomy in addressing real-world challenges. Through participation in PBL, students actively engage in inquiry, evaluate multiple solution options, and make decisions grounded in evidence [2]. Therefore, PBL represents an effective instructional approach for preparing students with key 21st-century competencies, including critical thinking, problem-solving, and collaborative learning skills [52]. Additionally, the greater uniformity of scores within the intervention group suggests that PBL has the potential to standardize learning outcomes across students, thereby minimizing achievement gaps in the classroom.

These results align with the SDGs, specifically SDG 4: quality education. By promoting student-centered and participatory learning, PBL supports the attainment of inclusive, high-quality education while enhancing HOTS [81]. Moreover, the critical thinking abilities developed through PBL correspond with SDG 8: decent work and economic growth, as graduates equipped with strong analytical and problem-solving skills are more capable of thriving in today's dynamic global workforce [82].

In addition, PBL aligns with SDG 16: peace, justice, and strong institutions, as students trained in critical and reflective thinking are better equipped to make evidence-based decisions, consider diverse perspectives, and actively contribute to the development of fair and democratic societies [83]. Therefore, this study emphasizes not only the academic benefits of PBL but also its significance within the global sustainable development framework. PBL can be regarded as a strategic pedagogical approach that improves learning quality while promoting human development marked by competitiveness, integrity, and a dedication to collective advancement. Therefore, the findings of this study have important significance in providing an empirical basis for strengthening learning practices oriented towards the development of HOTS and their contribution to sustainable development.

The significance of this study lies in its empirical evidence demonstrating that the PBL model effectively enhances students' HOTS, particularly critical thinking, as indicated by a statistically significant difference between the PBL and direct learning groups ($p<0.05$) and a substantial difference in mean scores. These findings confirm that PBL is not merely an alternative instructional approach but a powerful pedagogical strategy for fostering analytical, evaluative, and problem-solving competencies that are essential for 21st-century learning. Beyond its impact on learning outcomes, the implementation of PBL promotes active engagement, collaborative learning, reflective thinking, and learner autonomy, thereby providing practical guidance for educators and policymakers in integrating student-centered approaches into higher education curricula to improve learning quality [74], [84], [85]. Furthermore, the study contributes to broader educational goals by supporting the development of competencies aligned with the SDGs, particularly those

related to quality education, workforce readiness, and innovation. By strengthening critical, creative, and adaptive thinking skills, PBL facilitates the preparation of competent and globally competitive human resources capable of addressing complex challenges in rapidly changing environments.

4. CONCLUSION

The posttest results in the experimental group showed scores ranging from 16 to 23, with an average of 20.16 and a SD of 1.608. In contrast, the comparison group recorded scores between 14 and 21, resulting in an average of 17.14 and a SD of 1.948. The observed average difference of 2.72 points between the stimulus group and the comparison group indicates a significant increase in the stimulus group compared to the comparison group. In other words, there is a difference in the level of critical thinking between students who were treated with the PBL Model and students who were treated with the direct learning model. Students who were taught with PBL had a higher level of thinking compared to students who were taught with the direct learning model.

The results of the t-test indicate that the average difference produces a t-test score of 8.453 with 98 degrees of freedom and a two-way significance of 0.000 ($p<0.05$). This means that statistically, there is a significant difference between the post-test results of the stimulus group and the comparison group. The average difference of 3.020 indicates that the stimulus group achieved a higher average post-test score compared to the comparison group. These results indicate that the application of the PBL model has a significant impact on improving students' high-level critical thinking skills. Referring to the results of this study, further research can examine the integration of PBL with digital learning or technology-based approaches to further strengthen students' HOTS.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that there are no competing interests associated with the publication of this article.

DATA AVAILABILITY

The datasets underlying the results of this research can be obtained from the corresponding author upon reasonable request. Public access is restricted to ensure compliance with ethical standards and to safeguard the confidentiality of the research participants.

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