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# Impacts of Problem-Based Learning Towards Calculus Achievement and Mathematical Critical Thinking Skills Among Pre–University Students

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## Abstract

Pre-university students often struggle with calculus, particularly integration, and critical thinking skills, which are vital for industry needs. This study investigates the impact of problem-based learning (PBL) on calculus achievement and mathematical critical thinking skills among pre-university students. Using a control group and a quasi-experimental design, the research involved 48 pre-university college students. Participants were divided into two groups: 24 students received PBL instruction, while 24 students followed a conventional approach. Students' achievement in calculus and mathematical critical thinking skills was assessed through pre-tests, post-tests, and delayed post-tests. The analysis revealed a significant improvement in calculus achievement and mathematical critical thinking skills among students who experienced PBL compared to those who received conventional instruction. The findings suggest that PBL is more effective than conventional teaching methods, and its continued use in future educational settings is recommended.

**Keywords:** problem-based learning; achievement; critical thinking skills; mathematics; experimental study; pre-university.

## 1 Introduction

Malaysian students' persistent low performance in mathematics is evidenced by the declination score of the Trends in International Mathematics and Science Study (TIMSS) and the Programme for International Student Assessment (PISA). This is confirmed by Shin et al. [70], which shows that despite significant financial investments made in enhancing education in Malaysia, student achievement in mathematics has drastically decreased. The international mathematics achievement of Malaysia suggests that, generally, Malaysian students have yet to attain a solid grasp of fundamental mathematical concepts. This indicates that the overall level of mathematics achievement among those assessed in PISA and TIMSS during that period fell short of expectations, with some of them pursuing pre-university study and then going to university with inadequate proficiency in mathematics. Perhaps students at pre-university colleges continue to struggle with mathematics, particularly calculus, according to the needs analysis of pre-university students [37]. At the same time, Hoban [34] stated that most higher institutions also lack an understanding of basic calculus concepts, including pre-university students. Numerous studies have indicated that calculus poses a significant challenge for students [19]. Within calculus, integration and derivatives stand out as the two most formidable topics [75].

Meanwhile, Carnell et al. [18] have shed light on why students perceive calculus as intricate, highlighting insufficient prior knowledge as a contributing factor. The lecturer's role becomes crucial, especially during transitional phases like the higher institution stage such as pre-university, in emphasizing the importance of foundational mathematical concepts, particularly in calculus. This understanding is essential for students to grasp the subject at advanced levels [42]. In light of this situation, there is a necessity for educators at the pre-university level to ensure that students sufficiently master calculus before they advance to higher education level at university with a strong understanding of calculus. Diversifying student-centered learning strategies, such as the problem-based learning [3], utilizing technology like augmented reality in module [54], and incorporating tools such as GeoGebra in mathematics instruction [33], can significantly enhance students' mathematics achievement. Therefore, educators must implement innovations and changes in teaching and learning calculus so that students can better master calculus at the pre-university level.

A Research Institute of National Higher Education research claims that despite having excellent scores, many graduates cannot find employment that fits their skills [32]. Additionally, several companies have voiced concerns about specific graduates' attitudes, skills, and knowledge [60]. Critical thinking skills are among the competencies that graduates fail to achieve [58]. According to Hanapi et al. [31], a recent study demonstrates a significant gap between employability and thinking skills, particularly concerning graduates' critical thinking potential. Additionally, Nirmala and Kumar [56] emphasized that a career requires graduates to possess critical capacity. This problem has extended to higher institutions since students find it challenging to grow as critical thinkers [67]. Consequently, students have to obtain critical thinking abilities to meet the expectations of today's society. Critical thinking skills may be cultivated in a school context [15] specifically in mathematics [80]. Besides, several experts stated that thinking skills and student academic achievement are interrelated [53]. In this regard, students who learn using critical thinking skills frequently perform well in school [55]. Thus, to prepare students for future employment and improve academic achievement, educators ought to have a substantial role in aiding students in enhancing their critical thinking skills in pre-university study.

The lecturer's role at a pre-university college is to encourage students to achieve their full potential. Prior research indicates academic achievement and critical thinking skills are significantly correlated among college students [5]. However, Kassim and Zakaria [39] pointed out that several lecturers struggle to integrate critical thinking skills into their instruction since their teaching practices are not varied enough. Furthermore, the study also showed that teachers discovered less about thinking skills and how to employ them in the classroom [63]. The teaching approach is crucial to stimulate students' interest in mathematics [1]. Due to a conventional approach that primarily relies on lecture explanations of class material and homework assignments at all educational levels, only a few students participate in classroom activities [2]. In this framework, conventional lectures are given by the lecturer in front of the class using a teacher-centered technique. The actions taken in the classroom seem to follow the same pattern, according to Hadibarata and Rubiyatno [30], with the lecturer offering complete supervision and the students' only responsibility being to sit and listen to the explanation. It ignores the kids' cognitive growth, especially regarding thinking skills. As per the findings of Hong et al. [35] mathematics instruction might continue to follow a conventional approach that prioritizes classroom learning over letting students utilize their creativity and apply their knowledge to real-life situations. Teachers must change how they teach by adopting a student-centered approach to assist students.

Typically, assessments of mathematical achievements are administered in a classroom setting or via centralized assessment systems. Malaysia's PISA mathematics score is one indication of global mathematical proficiency. According to the Malaysian Ministry of Education, Malaysia's PISA mathematics literacy score declined 32 points from 2019 to $54th$ out of 81 countries [48]. The results indicate that Malaysia is still far from occupying one-third of the intended space. In addition, Malaysia participated in the global TIMSS assessment. Singapore and Malaysia took part in the TIMSS between 1999 and 2019, with Singapore having the highest average score. Malaysia fell much behind Singapore in average mathematics scores from 1999 to 2019 [81]. This suggests that there is still room for improvement in mathematics achievement as measured by TIMSS and PISA. The weak mastery of mathematical literacy among students at the school level contributes to a weak foundation in mathematics at the post-school level. The majority of post-school students continue their studies at the pre-university level such as form six, matriculation, university foundation program, A-levels, and International Baccalaureate [34]. Hence, students at the pre-university level encounter difficulties in learning calculus due to their weak foundation in mathematics at the school level. Besides, diverse stakeholders, including teachers, administrators, and curriculum drafters, have different opinions about student achievement in higher educational institutions. These stakeholders often consider that test scores on standardized measures influence student achievement [11]. As a result, authorities such as lecturers must play a significant role in improving mathematics success at the pre-university level.

Developing thinking skills, currently seen as crucial to national education, is one of the six objectives of the Malaysian Education Blueprints [47]. The two categories of thinking skills are higher-order thinking skills (HOTS) and lower-order thinking skills (LOTS) [43]. National education aims to use HOTS to produce students who can compete worldwide [44]. There is a scarcity of recent studies on thinking skills among post-secondary school students in Malaysia. The latest research by Ramli et al. [62] investigates the impact of the flipped classroom on creative thinking skills among higher institution students, which is a component of HOTS. In addition, one component of HOTS is critical thinking skills [12]. Developing critical thinking skills has become a top focus in mathematics curricula worldwide [13]. Critical thinking skills encompass communication and information abilities, along with the capacity to study, analyze, interpret, and evaluate data [46]. In contrast, Paul and Elder [59] characterize critical thinking as the enhancement of thinking skills specifically for analyzing and evaluating problem-solving scenarios. Germaine et al. [28] define critical thinking skills as the capability to engage in successful reasoning and identify connections across systems, concepts, and disciplines to solve problems and make judgments. Facione [22] further validates this framework by acknowledging five core areas of critical thinking, encompassing inference, analysis, identification, explanation, and evaluation. Only identification and evaluation are discussed in this study. A few researchers only included the domains of identifying information and evaluating evidence in mathematics subjects above their suitability compared to other domains that can be tested in other subjects [68]. Identification and interpretation based on Facione [22] involve the ability to grasp and articulate the meaning or importance of a diverse array of experiences, situations, data, events, judgments, conventions, beliefs, rules, procedures, or criteria. Within interpretation, there are sub-skills such as categorization, deciphering significance, and elucidating meaning. Perhaps, identifying and interpreting information in this study based on respondents can extract important information from the given problems and present it in the form of mathematical equations. Meanwhile, Facione [22] described evaluating evidence as evaluating the trustworthiness of statements or descriptions that reflect an individual's perception, experience, situation, judgment, belief, or opinion; and evaluating the logical coherence of the actual or intended inferential connections among statements, descriptions, inquiries, or other forms of representation. In short, evaluating evidence in this study refers to the ability of respondents to provide correct and accurate solutions and answers after reviewing the information provided through problems and conducting precise cross-checks. Thus, part of the effort to make students better thinkers is to promote their critical thinking ability.

According to Mursyid and Kurniawati [53], thinking skills have grown increasingly important in today's society, assisting individuals in coping with challenges. Thinking skills may also be crucial in many other industries, according to statistics from the National Association of Colleges and Employers on the significance of thinking skills for employment nowadays [23]. Numerous experts suggest a connection between students' academic achievement and their capacity for critical thinking [53]. A few research have been undertaken to underscore the importance of thinking abilities, particularly critical thinking skills. Numerous studies have demonstrated that improving students' critical thinking skills can enhance their performance in mathematics [10]. There are also studies indicating that the use of technology can promote thinking skills, particularly HOTS, among university students [45]. However, at the pre-university level, educators often overlook the aspect of developing critical thinking skills due to rushing through the syllabus and focusing on rote learning techniques. This neglects the development of soft skills including critical thinking abilities. Students require activities such as group discussions, presentation of ideas, and problem-solving, as well as communication among peers. Therefore, a shift needs to be implemented in helping students at the pre-university level to develop higher-order thinking skills (HOTS), including critical thinking abilities, in the classroom to support and improve their academic achievement and these skills.

Problem-based learning (PBL) emerges as a pedagogical strategy consistently employed by educators that attracts attention. This instruction concentrates the learning process around relevant real-world problems [4]. According to Faqiroh [24], PBL is a teaching strategy that can facilitate a variety of daily problems, including those that students may encounter. Tan [74], however, characterizes PBL as beginning the learning process with a problem. Butler and Wiebe [14] state that selecting the best solution and solving problems is typically a part of the PBL process. Therefore, to help students discover new information before working in small groups to solve difficulties, learning will begin with students dealing with problems. PBL incorporates facilitators who are either teachers or students. According to Salari et al. [65], the facilitator can also be considered an advisor who provides guidance and assistance. In PBL, the teacher must encourage students to investigate what they see using their prior knowledge rather than serving as an informant [29].

The focus of PBL is on the process of acquiring experience, social engagement and communication, and group cooperation rather than on solving a problem. To produce active involvement of each student, PBL encourages discussion and group activities. According to Yuan et al. [82], PBL involves working in small groups to find solutions to problems. Firdaus [25] stated students have to work collaboratively in groups during PBL. Kain [38] said that learning in small groups will be more helpful in facilitating the implementation of the PBL with the ratio of one teacher to ten students. In this study, PBL's model proposed by Barrows [8] emphasizes learning in small groups among students and is monitored by teachers acting as facilitators. Instead of concentrating on problem solutions, PBL emphasizes the process of gaining experience, social interaction and communication, and collaboration among peers. To generate active participation from every student, PBL promotes group activities and communication. Also, PBL entails problem-solving in small groups [83]. Based on Firdaus [25], group collaboration is required of students during PBL.

In comparison, Kain [38] claimed that studying in small groups will be more beneficial in promoting the adoption of PBL with a teacher-to-student ratio. The PBL model suggested by Barrows [8] is employed in this study, which highlights student learning in small groups and is administered by teachers serving as facilitators. This is seen in Figure 1 on the McMaster model developed by Barrows [8]. The treatment group will be divided into small groups consisting of four to five members and led by more knowledgeable others, MKO was appointed among selected students. MKO is somewhat self-explanatory; it refers to someone with a better understanding or a higher ability level than the learner of a particular task, process, or concept [40]. The problems were used as tools for problem-solving and as a stimulus to influence students' cognition. During this study, non-routine and open-ended problems in mathematics served as stimuli that resulted in heightened cognitive conflict. Student-centered learning occurred through active discussions in solving the given problems, with the teacher acting as a facilitator. As a result, information was obtained through self-directed learning, which can be retained longer and more effectively compared to the rote learning approach. MKO would assist peers more effectively as they only focus on small groups and are more focused and directed. Additionally, the problems used are non-routine and open-ended problems that focus more on real-life applications. These problems can stimulate cognitive development through group discussions facilitated by the MKO. Consequently, students will comprehend and master the given concepts more quickly through solving these problems. Furthermore, presenting solutions and answers can enhance students' critical understanding as they can identify and interpret the given problems, as well as provide justifications and evidence for their solutions through group presentations.

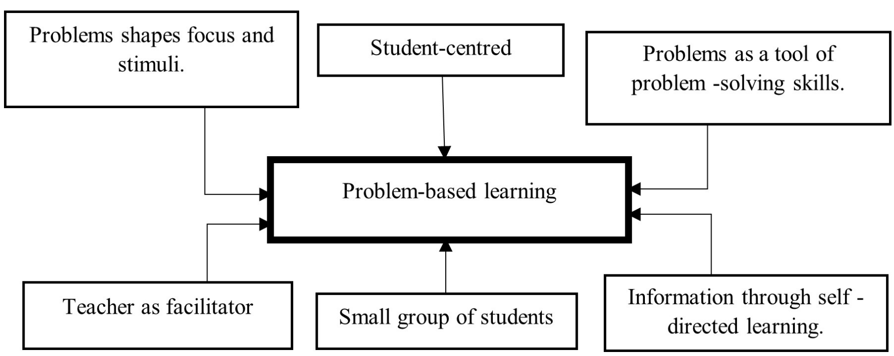



Figure 1: McMaster model.

At the same time, the PBL strategy in this study adopts the strategy by Arends [7]. Five phases in this strategy can be formulated as follows:

a) Student orientation on problems: At this stage, the teacher explains the learning objectives and the necessary logistics and motivates the learner to be actively involved in problem-solving.

b) Organizing students to learn: At this stage, the teacher divides the student into small groups, helping students define and organize problem-related learning tasks.

c) Guide the research (investigation) of individuals and groups: At this stage, the teacher encourages students to gather information corresponding to the problem encountered, implementing an investigative strategy to obtain problem-solving.

d) Develop and present problem-solving results: At this stage, the teacher helps the student develop and present problem-solving outcomes and helps the student divide the task with their friend.

e) Analyze and assess the problem-solving process: At this stage, the teacher assists the student in assessing and reflecting on the research and processes used in solving problems.

Numerous studies have shown the advantages of PBL for teaching and learning. Within PBL, learning happens due to self-discovery and in-questioning [74]. Self-discovery arises from group discussions and problems given by teachers. Furthermore, self-discovery may impact memory storage's long-term retention [69]. Additionally, PBL promotes collaborative problem-solving among students [20]. With that, problems are more accessible, relationships among group members are strengthened, and active class participation is encouraged [21]. Comparing PBL to conventional learning, the results of previous studies demonstrate that PBL may improve mathematics achievement [49]. Recent research has shown how PBL enhances critical thinking skills [52]. In conclusion, bringing PBL into practice may benefit students and help teachers facilitate more effective teaching and learning in school.

## 2 Research Objectives

This study sought to examine the impacts of PBL on pre-university students' mathematical achievement and critical thinking skills. Following the establishment of three research objectives, eight hypotheses were developed:

1. Compare the impacts of the PBL and conventional group on pre-university students' achievements (post-test and delayed post-test) in mathematics.
2. Compare the impacts of the PBL and conventional group on pre-university students' mathematical critical thinking skills (post-test and delayed post-test) in mathematics.
3. Compare the impacts of the PBL and conventional group on identifying information and evaluating evidence (post-test and delayed post-test) among pre-university students in mathematics

Research Hypothesis:

$H_{01}$ : There is no substantial difference in the mean scores of students' achievement tests at post-test between the PBL and conventional groups.

$H_{02}$ : There is no substantial difference in the mean score on students' achievement test at delayed post-test between the PBL and conventional groups.

$H_{03}$ : There is no substantial difference in the mean on students' mathematical critical thinking skills at post-test between the PBL and conventional groups.

$H_{04}$ : There is no substantial difference in the mean on students' mathematical critical thinking skills at delayed post-test between the PBL and conventional groups.

$H_{05}$ : There is no substantial difference in the mean on students' identifying information at post-test between the PBL and conventional groups.

$H_{06}$ : There is no substantial difference in the mean on students' identifying information at delayed post-test between the PBL and conventional groups.

$H_{07}$ : There is no substantial difference in the mean on students' evaluation of evidence at post-test between the PBL and conventional groups.

$H_{08}$ : There is no substantial difference in the mean on students' evaluating evidence at delayed post-test between the PBL and conventional groups.

In addition, the conceptual framework of the study is shown in Figure 2. From this framework, two groups were tested, and pre-tests were conducted before the experiment commenced. Following the intervention, post-tests and delayed post-tests were conducted to observe the intervention's impacts on calculus achievement and mathematical critical thinking skills, consisting of identifying information and evaluating evidence.

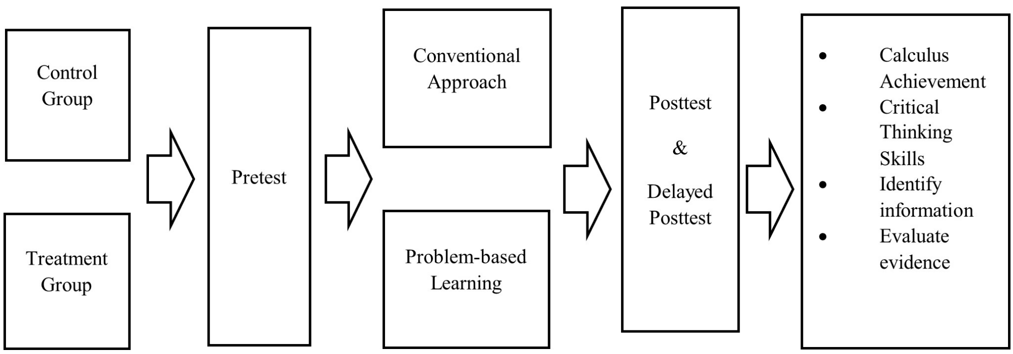



Figure 2: Conceptual framework.

## 3 Methodology

The quasi-experimental was performed in this study among pre-university students. They were separated into treatment and control groups. The study's quasi-experimental technique was chosen because it examines the causes and effects of PBL in mathematics instruction. The treatment group employed PBL, while the control group utilized a conventional approach. Both groups were given the same questions, materials, and notes during the experiment. The control group employed the conventional approach, using a teacher-centered approach. Meanwhile, the treatment group utilized PBL using the McMaster model and Arends' strategy. During the class activity, the treatment group would focus on group discussions on open-ended and non-routine problems, compared to the control group, which leaned more towards a teacher-centered approach, listening to the solutions of each problem given by their instructor. During group discussions, students in the treatment group were encouraged to present and defend their solutions and answers. The experimental study for both groups was carried out simultaneously beginning pre-test to delayed post-test. As for this research, intact groups must be used by the researchers. Due to unequal groups, this quasi-experimental design was established [16] and respondents were not involved in random selection [27]. This design is preferable since the students are in designated classes during the study and cannot be separated (intact group), which will affect the college timetable and the lecturers. Randomly allocating students to treatment and control groups will interfere with classroom learning [27]. Randomly assigning students to treatment and control groups will undermine classroom learning.

Nevertheless, a randomized approach is carried out by randomly selecting two tutorial groups from 90 tutorial groups because the statistical analysis for this study depends on inferential analysis. Table 1 illustrates the research design model utilized in this study. The research sample was chosen via purposeful sampling. Two classes of 48 pre-university students from two tutorials were randomly selected among 90 tutorials and divided into two groups of 24 students each. The student population was evenly distributed across each tutorial group.

Table 1: Quasi-experiment design.

| **Group** | **Pre-test** | | **Post-test** | **Delayed Post-test** |
|---|---|---|---|---|
| Conventional | $O_1$ | $X_1$ | $O_2$ | $O_4$ |
| | | | $O_3$ | $O_5$ |
| PBL | $O_1$ | $X_2$ | $O_2$ | $O_4$ |
| | | | $O_3$ | $O_5$ |

* $X_1$: Conventional approach; $X_2$: Treatment Group (Problem-based learning);
$O_1$: Pre-test; $O_2$: Post-test; $O_3$: Critical thinking skill (Post-test);
$O_4$: Delayed post-test; $O_5$: Critical thinking skill (delayed post-test).

Students were administered six-item questions for post-tests and delayed post-tests to evaluate their achievement. Seven experts validated these tests, yielding a score of 0.97. The total marks for calculus achievement for all tests are 60 marks. These marks were then calculated using the percentage obtained by each respondent's marks. Additionally, after the intervention, the students' mathematical critical thinking skills were assessed using a mathematical critical thinking skill rubric adapted from Firdaus [25] by developing a rubric from a scale of 0 to 4 specific based on the respondent's mathematics achievement test script. In mathematical critical thinking skills, identifying information and evaluating evidence are the two domains that are measured and in line with the study of Setambah [68]. The rubric is used in scoring mathematical critical thinking skills through student scripts on the post-test and delayed post-test as referred to in Table 2. There are four items to measure the domain of identifying information and also four items domain of evaluating evidence. The critical thinking skill score is calculated from the total score of both domains. Each respondent's script is marked using an adapted rubric and a score value will be given for each item tested from a scale of 0 to 4. For this rubric score, the lowest possible score is 0, and the highest is 4. This rubric is suitable for assessment in the Malaysian context because Malaysia has started using the band 1 to 6 method in classroom assessment recently. However, since this study adapts a rubric instrument from a previous study that used a score of 0 to 4, the researcher maintained the score or band from a previous study carried out by Firdaus [25] to facilitate marking the script. A pilot study was conducted earlier, and all the tests have been carried out. Every test has been implemented, having previously been part of a pilot study. Reliability values for the pre-test were 0.80, and the post-test and post-delayed test were 0.75 and 0.75, respectively. Meanwhile, the critical thinking skill rubric's post-test and delayed post-test reliability are 0.99. As a result, all of the study's instruments obtained good validity and reliability scores. In addition, the improvement incorporated the feedback into consideration.

Table 2: The holistic critical thinking scoring rubric.

| Measured aspects | Students' response to questions | Score |
|---|---|---|
| Identify and interpret information | Unable to find important facts and concepts from the question. | 0 |
| | Discover some of the important facts and concepts of the given question. | 1 |
| | Can find facts and concepts but cannot formulate problems. | 2 |
| | Finding important facts and concepts, can formulate problems, but not perfect. | 3 |
| | Discover important facts and concepts and can perfectly formulate problems. | 4 |
| Evaluate evidence and arguments | No attempt to perform procedural settlement. | 0 |
| | Performing settlement procedures or unclear settlement directions. | 1 |
| | Able to perform procedural settlement with a clear direction, but there are wrong facts or concepts in its use. | 2 |
| | Can perform the settlement procedure correctly but there is an error in performing the calculation or can perform the formula proof procedure, but there is an error in the use of the concept. | 3 |
| | Can perform the procedural settlement correctly, precisely in doing calculations or can perform procedural proof of formula correctly. | 4 |

Each group performed a pre-test to identify the primary difference between the treatment and control groups. The pretest served as a baseline for the variables being assessed and as a way of determining if there was a substantial difference between the means of the two groups. Consequently, the pre-test was incorporated into the study as a covariate. Problem-based learning was employed by the treatment group while the conventional approach was used by the control group. Six weeks later, the post-test assessed the students' achievement following the findings of the quasi-experimental study. The duration of the quasi-experimental study's procedure is contingent upon the type of intervention. Hua [36] notes that experimental studies require a significant investment of time and energy to yield meaningful results. This consideration is crucial, as a study period that is too brief may not fully reveal the effects of the treatment. Notably, Salam et al. [64] conducted a quasi-experimental study lasting six weeks, aligning with the timeframe of the current study. Two weeks following the post-test, the researcher administered a delayed post-test. The three aspects of data analysis are inferential analysis, descriptive statistics, and preliminary analysis. Preliminary data analysis techniques cover exploratory data analysis (EDA) and descriptive statistics. The exploratory data analysis conducted by both groups demonstrated that the achievement test score follows a normal distribution by using skewness, kurtosis, boxplot, histogram, and Q-Q plot. Descriptive statistics explained the participant distribution among the treatment and control groups. However, ANCOVA, MANCOVA, and further inferential statistics will address the study's issues. The first to fourth hypotheses were examined using ANCOVA, with the pre-test serving as a covariate and not encompassing any calculus achievement domains. Conversely, the fifth to eighth hypotheses were addressed using MANCOVA, with the pre-test acting as a covariate and encompassing two domains in critical thinking skills.

## 4 Finding and Analysis

This section covers the findings on the impact of PBL based on research objectives. Pre-test was used as a covariate in ANCOVA and MANCOVA analyses of the data. Table 3 displays the pre-university achievement test, showing both groups' mean and standard deviation (SD). In terms of achievement on the post-test, the treatment group outperformed the control group, with the treatment group ($M = 46.36$, $SD = 15.830$) surpassing the control group ($M = 35.13$, $SD = 17.984$). Additionally, on the achievement test at the delayed post-test, the treatment group ($M = 46.06$, $SD = 17.045$) surpassed the control group ($M = 35.50$, $SD = 15.131$).

Table 3: Descriptive data.

| **Tests** | **Group** | **Mean** | **Std. Deviation** | $N$ |
|---|---|---|---|---|
| Post-test | Control | 35.13 | 17.983 | 24 |
| | Treatment | 49.33 | 16.732 | 24 |
| Delayed post-test | Control | 35.50 | 17.045 | 24 |
| | Treatment | 48.04 | 14.266 | 24 |

The equality of variances in this study was assessed using Levene's test by referring to Table 4. During the post-test, Levene's test findings did not show statistical significance [$F(1, 46) = 3.222$, $p = .079 > .05$], demonstrating that the variance assumption's homogeneity was not violated. Additionally, no statistically substantial difference was observed at the delayed post-test of Levene's test [$F(1, 46) = 2.064$, $p = .158 > .05$], implying that there was no violation of the homogeneity of variance assumption.

Table 4: Equality's Levene test of error variances.

| **Test** | $F$ | $df1$ | $df2$ | **Sig.** |
|---|---|---|---|---|
| Post-test | 3.222 | 1 | 46 | .079 |
| Delayed post-test | 2.064 | 1 | 46 | .158 |

As controlling pre-test mean scores, Table 5 shows that in comparison to the control group, the treatment group's mean post-test scores differed significantly [$F(1, 46) = 14.239$, $p = .000 < .05$]. Likewise, a statistically significant difference was observed in the two groups in their achievement test scores on delayed post-test [$F(1, 46) = 14.053$, $p = .001 < .05$].

These findings demonstrated that compared to students in the control group, students in the treatment group significantly outperformed them on the post-test and delayed post-test. Then, $H_{01}$ and $H_{02}$ should be rejected. While controlling for pre-test, there are significant differences between the treatment and conventional groups' means of achievement test scores at post-test and delayed post-test in mathematics among pre-university students.

Table 5: Equality's Levene test of error variances.

| Test | Source | Type III Sum of Squares | *df* | Mean squares | *F* | Sig. | Partial Eta Squared |
|---|---|---|---|---|---|---|---|
| Post-test | GROUP | 2626.294 | 1 | 2626.294 | 14.239 | .000 | .240 |
| Delayed post-test | GROUP | 2054.345 | 1 | 2054.345 | 14.053 | .001 | .238 |

Table 6 depicts the mean and standard deviation of the two groups' mathematical critical thinking skills among pre-university students. On the post-test, the treatment group ($M = 16.67$, $SD = 8.651$) performed better in mathematical critical thinking than the control group ($M = 11.92$, $SD = 8.727$). Additionally, at the delayed post-test, the treatment group ($M = 16.63$, $SD = 6.658$) outperformed the control group ($M = 10.71$, $SD = 10.373$), indicating higher mathematical critical thinking skills.

Table 6: Descriptive data for critical thinking skills.

| Test | Group | Mean | Std. Deviation | *N* |
|---|---|---|---|---|
| Critical thinking skills (post-test) | Control | 11.92 | 8.727 | 24 |
| | Treatment | 16.67 | 8.651 | 24 |
| Critical thinking skills (delayed post-test) | Control | 10.71 | 10.373 | 24 |
| | Treatment | 16.63 | 6.658 | 24 |

The equality of variances in this study was tested using Levene's test as in Table 7. The findings of Levene's test indicated that the mathematical critical thinking skills at the post-test $[F(1, 46) = .629, p = .432 > .05]$ were not significant, suggesting that the homogeneity of variance assumption was not violated. Additionally, there was no statistically significant difference in the delayed post-test results of Levene's test for mathematical critical thinking skills $[F(1, 46) = 3.777$, $p = .058 > .05]$, showing that there was no violation of the homogeneity of variance assumption.

Table 7: Equality's Levene test of error variances in critical thinking skills.

| Test | *F* | *df*1 | *df*2 | Sig. |
|---|---|---|---|---|
| Critical thinking skills (post-test) | .629 | 1 | 46 | .432 |
| Critical thinking skills (delayed post-test) | 3.777 | 1 | 46 | .058 |

The mean score for mathematical critical thinking skills was significantly different between the treatment and control groups at the post-test, as depicted by Table 8 $[F(1, 46) = 6.617$, $p = .013 < .05]$, even after controlling for pre-test mean scores. In addition, a statistically significant difference was observed between the two groups in the results of the delayed post-test for mathematical critical thinking skills $[F(1, 46) = 8.459, p = .006 < .05]$. The post-test and delayed post-test findings revealed that students in the treatment group performed much better in mathematical critical thinking skills than students in the control group. Hence, the $H_{03}$ and $H_{04}$ should be rejected. Therefore, after controlling pre-test scores, there are significant differences in the means of the students' mathematical critical thinking skills at the post-test and delayed post-test between the treatment and conventional groups.

Table 8: Tests of between-subject effects of critical thinking skills.

| Test | Source | Type III Sum of Squares | *df* | Mean squares | $F$ | Sig. | Partial Eta Squared |
|---|---|---|---|---|---|---|---|
| Critical thinking skills (post-test) | GROUP | 305.292 | 1 | 305.292 | 6.617 | .013 | .128 |
| Critical thinking skills (delayed post-test) | GROUP | 457.172 | 1 | 457.172 | 8.459 | .006 | .158 |

The two domains of critical thinking skills are identifying information and evaluating evidence. Table 9 displays pre-university students' mean and standard deviation in identifying information and assessing evidence. At the post-test, the treatment group's identifying information score ($M = 8.63$, $SD = 4.402$) was higher than that of the control group ($M = 6.25$, $SD = 4.346$). At the post-test, the treatment group ($M = 8.04$, $SD = 4.268$) outperformed the control group ($M = 8.58$, $SD = 3.387$) in evaluating evidence. In addition, the treatment group ($M = 8.58$, $SD = 3.387$) outperformed the control group ($M = 5.54$, $SD = 5.217$) during the delayed post-test, demonstrating higher identifying information. The treatment group outperformed the control group ($M = 5.13$, $SD = 5.203$) on the delayed post-test ($M = 8.04$, $SD = 3.303$), implying higher evaluating evidence.

Table 9: Descriptive data.

| Tests | Group | Mean | Std. Deviation | $N$ |
|---|---|---|---|---|
| Identifying information | Control | 6.25 | 4.346 | 24 |
| (post-test) | Treatment | 8.63 | 4.402 | 24 |
| Evaluating evidence | Control | 5.67 | 4.410 | 24 |
| (post-test) | Treatment | 8.04 | 4.268 | 24 |
| Identifying information | Control | 5.54 | 5.217 | 24 |
| (delayed post-test) | Treatment | 8.58 | 3.387 | 24 |
| Evaluating evidence | Control | 5.13 | 5.203 | 24 |
| (delayed post-test) | Treatment | 8.04 | 3.303 | 24 |

Levene's test evaluated the investigation's equality of variances as displayed in Table 10. The results of Levene's test demonstrated that the variance assumption's homogeneity hadn't been violated, indicating the identifying information at the post-test was not significant [$F(1, 46) = .219$, $p = .642 > .05$]. The variance assumption's homogeneity was also not violated, as evidenced by Levene's test results, which revealed that the evaluating evidence at the post-test was also not significant [$F(1, 46) = 1.796$, $p = .187 > .05$]. Additionally, the findings of Levene's test for identifying information showed no statistically significant difference in the delayed post-test [$F(1, 46) = 3.975$, $p = .052 > .05$], indicating that the homogeneity of variance assumption was also not violated. Finally, the result also showed that there was no statistically significant difference in delayed post-test results of Levene's test for evaluating evidence [$F(1, 46) = 3.734$, $p = .059 > .05$], indicating that there was no violation of the homogeneity of variance assumption.

Table 10: Levene's test of equality of error variances of identifying information and evaluating evidence.

| **Test** | $F$ | $df1$ | $df2$ | **Sig.** |
|---|---|---|---|---|
| Identifying information (post-test) | .219 | 1 | 46 | .642 |
| Evaluating evidence (post-test) | 1.796 | 1 | 46 | .187 |
| Identifying information (delayed post-test) | 3.975 | 1 | 46 | .052 |
| Evaluating evidence (delayed post-test) | 3.734 | 1 | 46 | .059 |

After controlling for the pre-test mean scores on the post-test, Table 11 demonstrates a statistically substantial difference in the mean of identifying information between the treatment and control groups $[F(1, 46) = 6.556, p = .014 < .05]$, suggesting that $H_{05}$ has to be rejected. Additionally, the findings also showed a significant difference in post-test in the means of evaluating evidence on both groups $[F(1, 46) = 6.554, p = .014 < .05]$. Consequently, $H_{07}$ also needs to be rejected. Therefore, when controlling for pre-test scores, there is a significant difference in the mean of the treatment group and the conventional group at the post-test for identifying information and evaluating evidence.

Likewise, the findings also showed there is a statistically significant difference between the two groups in the results at the delayed post-test for identifying information $(F(1, 46) = 8.744$, $p = .005 < .05)$, indicating $H_{06}$ has to be rejected. At the delayed post-test, the mean of evaluating evidence between the treatment and control groups differed significantly, according to the results $[F(1, 46) = 8.176, p = .006 < .05]$, showing $H_{08}$ should not be accepted. The treatment and conventional groups differ significantly in identifying information and evaluating evidence at the delayed post-test despite controlling for pre-test mathematics scores. According to these findings, students in the treatment group significantly outperformed those in the control group on the post-test and delayed post-test for both domains.

Table 11: Tests of between-subject effects of identifying information and evaluating evidence.

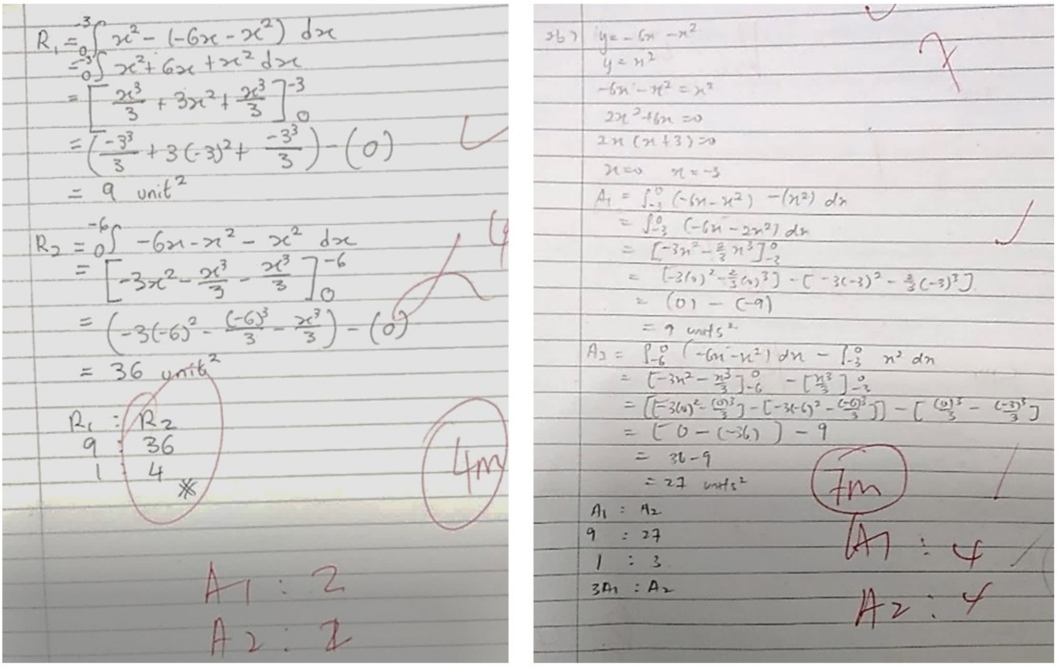
| **Test** | **Source** | **Type III Sum of Squares** | $df$ | **Mean squares** | $F$ | **Sig.** | **Partial Eta Squared** |
|---|---|---|---|---|---|---|---|
| Identifying information (post-test) | GROUP | 76.405 | 1 | 76.405 | 6.556 | .014 | .127 |
| Evaluating evidence (post-test) | GROUP | 76.241 | 1 | 76.241 | 6.554 | .014 | .127 |
| Identifying information (delayed post-test) | GROUP | 120.610 | 1 | 120.610 | 8.744 | .005 | .163 |
| Evaluating evidence (delayed post-test) | GROUP | 111.159 | 1 | 111.159 | 8.176 | .006 | .154 |

## 5 Discussion

According to Syah [73], each student can achieve a specific level in the classroom. Nonetheless, it's commonly asserted that teachers are responsible for assisting learners to attain their full potential, including developing their cognitive, emotional, and psychomotor skills [57]. Thus, one of the primary goals of implementing PBL in the classroom was to enhance learning achievement and foster the development of critical thinking skills. This study investigated the impact of PBL and the conventional approach among pre-university students. The findings indicated that students in the treatment group performed better than those in the control group, as seen during the post-test and delayed post-test. According to the results, PBL can improve students' mathematical achievement [50]. This is because PBL is one of the student-centered learning strategies [78]. Through student-centered learning, all students will be actively engaged in the learning process. Students are free to express opinions and ideas or challenge their peers' views with arguments and evidence. Through this active discussion, it can further strengthen students' concepts and understanding, thus enhancing their calculus achievement.

Additionally, PBL encourages student participation in the classroom by having them discuss the assigned problems [61]. In PBL group discussions throughout this study, HOTS problems were given greater emphasis. Group discussion can further strengthen the student's understanding of the subject matter [77]. The scaffolding process is encouraged by discussions in small groups conducted by a facilitator or MKO among selected students [84]. This study demonstrates that students who participated in PBL-facilitated group discussions, interactions, and solution presentations scored higher on HOTS questions. Previous studies showed that PBL could improve students' HOTS in mathematics [71]. Additionally, the findings also demonstrate a substantial difference among the two groups on the delayed post-test. This suggests that PBL can improve students' long-term memory effects and retention. Long-term effects on student achievement are one of PBL's benefits [17].

On the post-test and delayed post-test, the students who utilized PBL had significantly higher scores in mathematical critical thinking skills than the control group. This can be observed from the comparison of scripts marked in Figure 3. These scripts indicate that students in the PBL group scored significantly higher than the conventional group in both domains. A1 represents the domain of identifying information. The respondent from the control group (a) did not manage to identify the correct ratio of two region areas. Meanwhile, respondents from treatment group (b) managed to identify the correct ratio between the two region areas. Besides, A2 represents the domain of evaluating the evidence. The respondent from treatment group (a) managed to show the correct solution and answer for both regions and using the correct concept of integration. Compared to the respondent from the control group (b), he was not able to use the correct concept of integration by obtaining a negative value for the area. By comparing PBL to conventional learning, research indicates that PBL helps improve critical thinking skills [72]. One thing contributing to students' inability to think critically is instructional strategies that don't use high-level cognitive problems [51]. Teachers rarely employ instruction incorporating high-level cognitive questions that promote critical thinking [76], resulting in students lacking the critical thinking skills necessary to address real-world problems [9]. At the same time, the emphasis on the present conventional approach is more focused on low-level cognitive concerns such as memorizing and understanding, which is more focused on LOTS [6]. Thinking skills among students cannot be developed in a more critical direction when questions are used at this low-level [41].



(a) (b)

Figure 3: Comparison of candidate scripts between (a) PBL group and (b) conventional group.

Students were exposed to HOTS topics and problems connected to real-life situations during PBL. The students also brainstormed in groups to discover solutions to the problems presented. Students' high-level problem-solving skills, teamwork opportunities, and active learning activities contribute to developing critical thinking skills [79]. Students in the PBL group have also presented views, ideas, and solutions for each given problem. Each group member is free to critique and provide different perspectives and solutions. However, students are also free to defend their solutions with their arguments. Nonetheless, the lecturer will intervene if an incorrect solution is formulated by the group. Through this presentation and active discussion, it can enhance critical thinking skills in mathematics, particularly for both domains. The results indicate a significant difference between the two groups in identifying information and evaluating evidence on the post-test and delayed post-test. These results are consistent with research by Firdaus et al. [26] and Saputra et al. [66], demonstrating how problem-based learning may improve identifying information and evaluating evidence in critical thinking skills in the classroom.

## 6 Conclusion

The discussion and findings indicate that problem-based learning is a viable alternative to the conventional approach. The findings indicate that problem-based learning can strengthen students' concepts and understanding of calculus, thereby improving performance in calculus. Additionally, problem-based learning has been found to develop mathematical critical thinking skills, particularly in the domains of identifying information and evaluating evidence. The findings of this study are also in line with previous research. Given the significance of mathematical achievement and critical thinking skills in producing a thinking-capable generation, the findings of this study contribute to the body of knowledge regarding the use of empirical evidence to assess students' critical thinking skills in mathematics learning at pre-university students. This study also revealed that problem-based learning improves students' mathematical achievement and critical thinking skills, notably in identifying information and evaluating evidence. To achieve national education goals, educators must adapt and alter the paradigm in mathematics instruction by adopting problem-based learning. Careful changes must be undertaken by applying problem-based learning in classroom activities to provide students with the opportunity and support so that they will master mathematics by the time they graduate.

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**Conflicts of Interest** The authors declare that there is no conflict of interest regarding the publication of this article. All aspects of this research, including data collection, analysis, and interpretation, were conducted with the highest standards of academic integrity and transparency. The findings and conclusions presented in this study are solely the result of our independent scholarly work, free from any external influence or bias.

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