



A Problem-Based Learning Approach to Calculus 1 using Students Workbooks and Digital Visualization as Instructional Media

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ABSTRACT

BACKGROUND & CONTEXT

Calculus is a core component of engineering curricula, yet many first-year students struggle to meet expected performance levels due to weak mathematical foundations and limited problem-solving experience. The literature highlights the importance of scaffolding and active learning to strengthen conceptual understanding in mathematics.

PURPOSE OR GOAL

This study aimed to evaluate the effectiveness of structured learning tools in improving student achievement in Calculus 1. Specifically, it examined whether engagement with problem-based Student Workbooks and digital visualization resources supports attainment of Course Learning Outcomes (CLOs). The central question was whether consistent effort in completing Workbook exercises correlates with CLO exam scores.

APPROACH OR METHODOLOGY

A structured Student Workbook aligned with the Calculus 1 CLOs was implemented. Students' Workbook practice scores were collected and compared with their performance on four CLO-based examinations. Correlation analysis and graphical visualization were applied to assess the relationship between structured practice and exam achievement.

OUTCOMES

Findings revealed a moderate positive correlation ($r = 0.41\text{--}0.55$) between Workbook engagement and CLO exam performance, particularly for CLO2 and CLO4. Students who completed more practice tasks consistently achieved higher scores.

CONCLUSIONS

The results support the integration of problem-based Workbooks and visualization tools in Calculus instruction, aligning with existing evidence that structured scaffolding and active learning enhance conceptual understanding.

KEYWORDS

Calculus education, problem-based learning, instructional Student Workbook.

Introduction

Basic mathematical skills are widely recognized as a crucial determinant of student success in higher-level mathematics courses. In particular, a strong foundation in basic mathematics is essential for mastering Calculus, as it equips students with the procedural fluency and conceptual understanding needed to engage with more advanced topics. Calculus is a foundational subject in engineering education, yet it remains one of the most challenging courses for first-year students. At the Telecommunication Engineering Program, student performance in Calculus has consistently been below expectation, with a significant number failing to meet the minimum learning outcomes. In the 2024/2025 academic year, 34.25% of students received grades D or E in Calculus 1 (odd semester), while 23.59% of students received grades D or E in Calculus 2 (even semester). These statistics highlight the urgent need for more effective instructional approaches to support student learning.

Instruction in Indonesia still faces several limitations. One persistent issue is the lack of opportunities for students to engage in structured mathematical writing, even though written expression is widely recognized as a powerful means to clarify reasoning and solidify abstract concepts. Mathematics learning that emphasizes writing—such as explaining solution steps, justifying procedures, and reflecting on problem-solving strategies—has been shown to improve deeper comprehension and reduce reliance on rote memorization. To address this gap, the use of structured learning Student Workbooks has gained attention as an effective scaffold, enabling students to practice mathematical writing systematically while progressing through complex topics at their own pace.

Building on this foundation, Problem-Based Learning (PBL), conceptualized as an instructional model that facilitates learning through the resolution of authentic, real-world problems, has emerged as a particularly promising approach. By engaging students in real-world problems, PBL fosters deeper understanding and retention of mathematical concepts. Recent studies have demonstrated the effectiveness of PBL in enhancing student engagement and performance in calculus courses. For example, Ramli et al. (2024) reported that PBL implementation in undergraduate mathematics significantly improved students' ability to transfer knowledge to unfamiliar contexts. PBL also encouraged collaborative learning and increased persistence among engineering students in difficult mathematics topics (Suryanti et al., 2024). Moreover, integrating PBL with digital visualization tools such as GeoGebra and CalcPlot3D has been shown to improve students' understanding of abstract calculus concepts by bridging symbolic and graphical representations (Medina Herrera et al., 2024; Ziatdinov & Valles Jr, 2022).

Scaffolding, another complementary instructional strategy, provides temporary support to students as they develop new skills and knowledge. Research has highlighted that scaffolding techniques—such as guided practice, formative feedback, and gradually reduced support—can significantly enhance students' problem-solving abilities in mathematics. Digital scaffolding in calculus instruction has been shown to improve engagement and conceptual accuracy (Biza, González-Martin & Pinto, 2022), while structured scaffolding promoted autonomy and deep learning in engineering mathematics courses. The combination of PBL and scaffolding thus creates a learning environment that encourages active participation and critical thinking, which are essential for mastering calculus (Prabawanto, 2017).

The COVID-19 pandemic has further exacerbated challenges in mathematics education. Disruptions to traditional classroom instruction have led to significant learning gaps, particularly in foundational subjects like calculus. Studies reported declines in mathematical skills and increased failure rates in calculus courses during the pandemic (Mendoza Velazco et al., 2021). For instance, Dirgantoro & Soesanto (2021) found that students learning calculus online experienced significantly lower engagement and mastery of concepts compared to pre-pandemic cohorts. Similarly, Mendoza Velazco et al. (2021) documented increased anxiety and reduced performance in mathematics among engineering students in hybrid learning

models. These findings underscore the urgent need for innovative teaching approaches that can effectively support students in remote and hybrid learning environments.

This study responds to these challenges by explicitly integrating three complementary strategies—PBL, scaffolding, and digital visualization—into a unified instructional design for Calculus 1. While previous research has often examined these approaches individually, their combined implementation remains underexplored, particularly within the context of Indonesian engineering education. In response, this study explores the implementation of a PBL approach to Calculus 1, utilizing structured Student Workbooks and digital visualization tools as instructional media. The primary objective is to examine the impact of this integrated approach on students' understanding and performance in calculus. By analyzing the correlation between students' engagement with the Student Workbooks and their exam scores, the study aims to provide empirical evidence on the effectiveness of combining PBL, scaffolding, and digital visualization in calculus instruction.

The findings of this study have the potential to inform instructional practices in engineering education, particularly in the design and delivery of calculus courses. By leveraging PBL and scaffolding strategies, educators can create more engaging and effective learning experiences that address the diverse needs of students. Furthermore, the integration of digital visualization tools can enhance students' conceptual understanding, making calculus more accessible and less intimidating.

Methodology

Participants

The participants of this study were 123 first-year students from the Telecommunication Engineering Program at Telkom University, who were enrolled in Calculus 1 during the odd semester of the 2024/2025 academic year.

Intervention Design

This study adopted a structured learning Student Workbook titled *Modul Kalkulus 1* as an instructional intervention aimed at improving students' conceptual understanding and performance in Calculus 1. The Student Workbook was designed as a scaffolding tool that offers step-by-step guidance to help students develop problem-solving strategies. The intervention was implemented over the course of one semester (14 weeks). During this period, students were required to utilize the Student Workbook in both weekly face-to-face class meetings and independent study sessions. Each week, the instructor facilitated one to two sections of the Student Workbook, while students were expected to complete the corresponding follow-up exercises outside of class.

The content of the Student Workbook is organized thematically and progressively, starting from fundamental topics such as real number systems, inequalities, and elementary functions, before advancing to core calculus concepts such as limits, continuity, derivatives, and their applications. Each section consists of concise theoretical explanations, worked examples, visualizations (including number lines and function plots), and structured problem sets aligned with specific CLOs. This scaffolding approach was intended to shift students away from rote memorization toward conceptual mastery.

In addition to the printed materials, the Student Workbook was complemented by digital visualization tools, particularly GeoGebra, which were made accessible through the university's Learning Management System (Moodle). These tools allowed students to engage with dynamic representations of functions, limits, and derivatives, both during classroom activities and in independent practice.

Data Collection

During the implementation phase, students were required to engage with the Student Workbook both in-class and independently. Instructors monitored engagement through students' written responses, problem-solving steps, and reflections within the Student Workbook. These written outputs were also used to identify common misconceptions and inform instructional feedback.

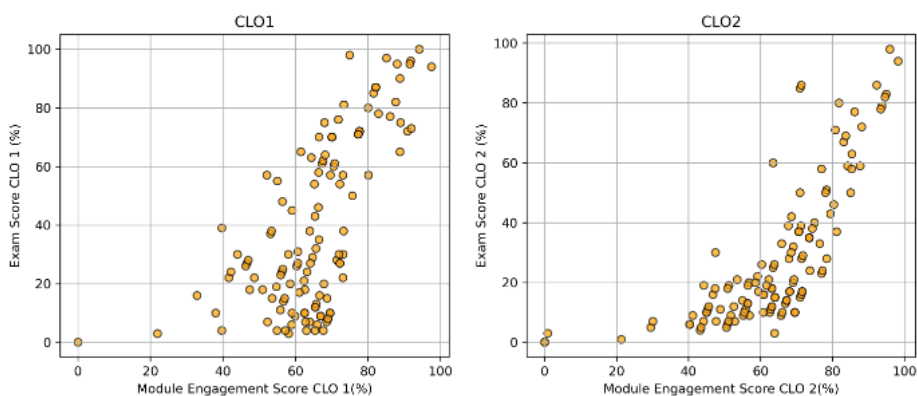
Data collection consisted of students' practice scores from the Student Workbook, as well as their performance in CLO-based examinations conducted at the end of the semester. A correlational analysis was conducted to examine the relationship between Student Workbook engagement and CLO achievement. Additionally, a qualitative analysis of students' written justifications was used to triangulate the quantitative findings and provide further insights into learning patterns.

Methodological Rationale

The methodological approach in this study was informed by previous research highlighting the value of modular and problem-based instruction in mathematics education. For example, Rahayu and Wulandari (2019) found that well-structured Student Workbooks significantly improved students' understanding of mathematical concepts. Similarly, Putri and Hidayat (2020) demonstrated that problem-based learning Student Workbooks enhanced students' motivation and problem-solving skills compared to traditional methods. The combination of structured practice and visual learning in *Modul Kalkulus 1* is consistent with best practices recommended in recent literature.

Result and Discussion

This study explored the impact of structured Student Workbook practices on student performance in Calculus 1, measured through exam scores mapped to Course Learning Outcomes (CLOs). Figure 1 presents scatter plots that depict the relationship between students' Student Workbook practice scores and their corresponding exam scores for CLO1 through CLO4. The plots reveal a positive trend across all CLOs, whereby students who engaged more actively with Student Workbook practices tended to score higher in their exams. This trend is most evident in CLO2 (Derivatives) and CLO4 (Applications), where the Student Workbook's structure and visual scaffolding appear to be especially effective in fostering procedural–conceptual fluency.



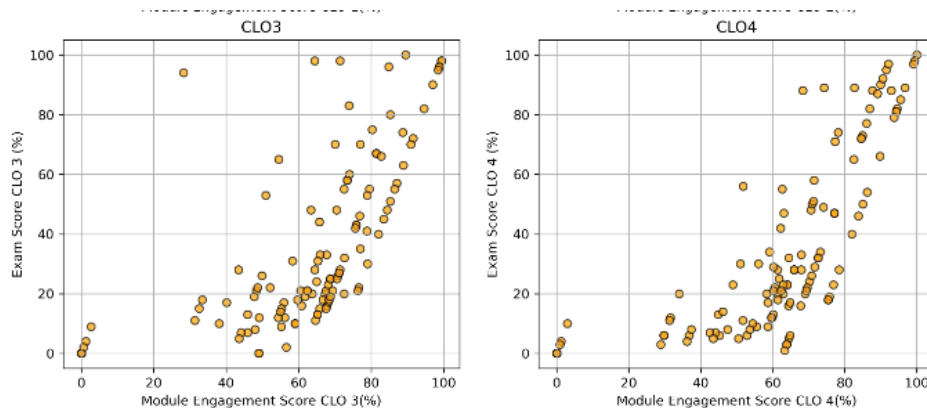


Figure 1: Relationship between Student Workbook Engagement and Exam Scores for Each CLO

Notably, while all CLOs show strong correlations, the scatter plots indicate relatively fewer cases of students with high practice scores but low exam performance. This consistency suggests that most students were able to translate their practice efforts into exam success, demonstrating the efficacy of the instructional design and scaffolding embedded within the Student Workbooks.

These results affirm the effectiveness of problem-based learning (PBL) implemented through modular instruction. The scaffolding strategies embedded in the Student Workbooks likely guided students through complex problems effectively, reinforcing understanding via repetition and structured reasoning. Features such as worked examples, visual aids, and progressively challenging exercises probably contributed significantly to procedural fluency and conceptual clarity.

These findings are in line with previous research highlighting the benefits of scaffolded practice and visualization tools in enhancing mathematics learning. For example, Ziatdinov and Valles Jr. (2022) showed that GeoGebra-based activities strengthen students' conceptual understanding of calculus, while Medina Herrera et al. (2024) stressed the importance of 3D visualization for connecting symbolic and spatial reasoning. Building on this evidence, our study demonstrates that integrating PBL, scaffolding, and digital visualization within a unified Student Workbook framework produces greater improvements in differentiation-focused outcomes (CLO2 and CLO4).

These findings are consistent with prior literature on the benefits of structured learning Student Workbooks in mathematics education. Studies by (Arici & Yilmaz, 2023), (Bozkurt Altan & Tan, 2021), and (Tractenberg et al., 2024) emphasize that guided practice combined with reflective components significantly enhances students' abilities to internalize mathematical concepts and apply them effectively in diverse contexts.

In summary, the analysis strongly supports the hypothesis that sustained engagement with structured, problem-based Student Workbooks is positively correlated with student achievement in Calculus. The integration of visual and statistical analyses underscores that differentiation-focused CLOs (CLO2 and CLO4) gain the greatest advantage from this instructional design. At the same time, the evidence highlights the effectiveness of these tools in closing conceptual gaps and enhancing CLO achievement. Nonetheless, the observed variation across CLOs points to areas for improvement, particularly in better aligning Student Workbook activities for CLO1 and CLO3 with exam requirements. Overall, these findings strengthen the case for embedding active learning strategies and continuous formative assessment in introductory engineering mathematics courses.

The strong correlations support the hypothesis that student effort, reflected in Student Workbook practice scores, is a significant predictor of learning achievement. This aligns with

existing research highlighting that structured, scaffolded learning materials, combined with problem-based learning approaches, enhance conceptual understanding and retention.

To further quantify this relationship, Pearson correlation coefficients were computed. As shown in Figure 2 (correlation heatmap), the correlations for CLO1, CLO2, CLO3, and CLO4 are 0.70, 0.80, 0.66, and 0.78 respectively. These values indicate strong positive correlations across all learning outcomes, with the strongest relationships observed in CLO2 and CLO4. The higher gains observed in CLO2 and CLO4 may be attributed to the effectiveness of scaffolding and visualization in addressing topics that demand strong connections between symbolic procedures and geometric interpretations, particularly in concepts such as slope, rate of change, and optimization problems.

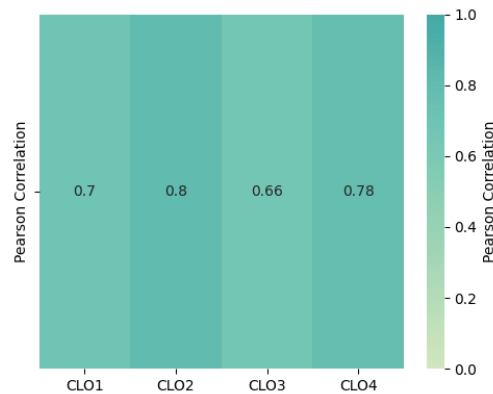


Figure 2: Correlation between Student Workbook Practice and Exam Score per CLO

While CLO3 shows a slightly lower but still strong correlation (0.66), CLO1 exhibits the lowest correlation among the four (0.70), though still substantial. These differences might reflect some variability in alignment between the practice Student Workbooks and the exam content for these CLOs, or differences in cognitive demands between practice tasks and assessments. This suggests opportunities for further refinement of instructional design, particularly for CLO3 and CLO1, to better synchronize practice activities with exam expectations.

From an instructional standpoint, these results validate the use of modular and scaffolded learning resources in Calculus instruction. They reinforce the importance of consistent student engagement in structured practice activities to bridge the gap between theoretical understanding and exam performance. The findings also recommend that educators focus on providing personalized feedback and additional support for CLOs where correlations are comparatively lower.

In conclusion, the strong and consistent correlations shown by the heatmap indicate that the integration of problem-based learning Student Workbooks positively impacts student achievement in Calculus 1. These findings provide empirical evidence to support the expansion of structured and scaffolded Student Workbooks in mathematics education, especially in foundational courses where early interventions significantly influence learning trajectories.

Prior to the implementation of the Student Workbook and the Calculus 1 lecture, students were administered a Basic Mathematics pretest to assess their basic mathematics abilities. This pretest served as an important diagnostic tool for capturing core competencies, ensuring that variations in calculus performance could be more accurately interpreted based on students' prior knowledge. To evaluate the impact of students' Basic Mathematics and their engagement with the Student Workbook on Calculus performance, a series of statistical analyses were carried out. The analysis began with descriptive statistics to summarize student performance across the three measures — Basic Math, Student Workbook, and Calculus 1 — followed by

correlation analysis to examine the strength and direction of their interrelationships. Figure 3 shows the heatmaps of correlation between Basic Math, Student Workbook, and Calculus 1.

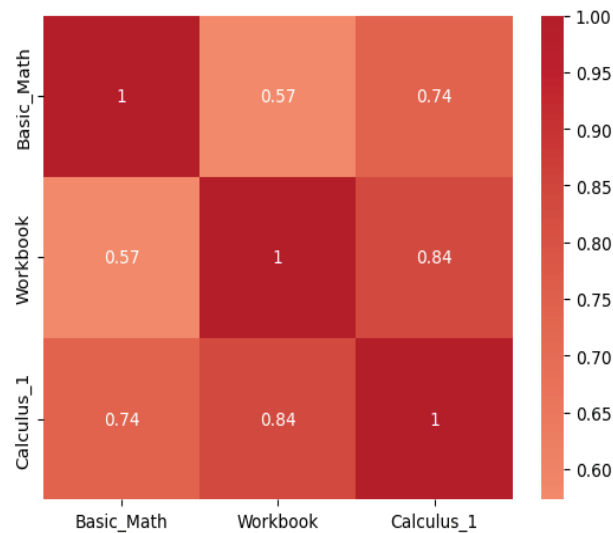


Figure 3: Heatmaps of the Pearson correlation coefficients among Basic Math, Workbook, and Calculus 1

The heatmap in Figure 3 illustrates the Pearson correlation coefficients among Basic Math, Workbook, and Calculus 1. All variables exhibit strong positive associations. The correlation between Basic Math and Calculus 1 is 0.74, indicating that students with stronger fundamental mathematical skills tend to achieve higher scores in calculus. The correlation between Workbook and Calculus 1 is even stronger at 0.84, highlighting the substantial role of workbook engagement in supporting calculus performance. Meanwhile, the moderate correlation of 0.57 between Basic Math and Workbook suggests that students with stronger foundational skills are also more likely to perform better on the workbook tasks. Overall, the heatmap provides evidence that both prior mathematical knowledge and structured workbook activities play important roles in students' achievement in calculus.

To further examine the relationships observed in the correlation analysis, a multiple linear regression was conducted with *Calculus* scores as the dependent variable and *Basic Math* and *Workbook* scores as independent variables. This approach allows us to quantify the unique contribution of each predictor while controlling for the other. The resulting regression model can be expressed as:

$$\text{Calculus} = -10.81 + 0.34 \times \text{Basic Math} + 0.69 \times \text{Students Workbook}.$$

The model was statistically significant, $F(2,120) = 240.9$, $p < .001$, and explained approximately 80.1% of the variance in Calculus scores (Adjusted $R^2 = 0.797$). Both predictors contributed positively and significantly, indicating that higher performance in *Basic Math* and greater engagement with the Student *Workbook* are associated with improved outcomes in Calculus 1. Figure 4 shows scatterplot matrix displaying the relationships among Basic Math, Student Workbook, and Calculus 1.

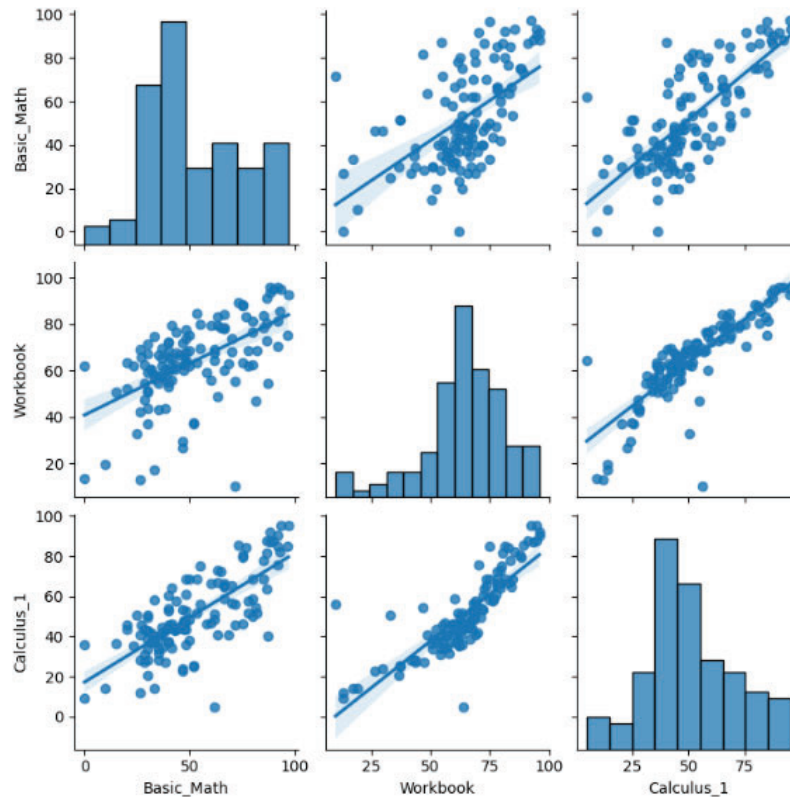


Figure 4: Scatterplot matrix displaying the relationships among Basic Math, Student Workbook, and Calculus 1

The scatterplot matrix in Figure 4 illustrates clear positive linear relationships among Basic Math, Student Workbook, and Calculus 1. Students with higher Basic Math scores tend to achieve better results in both the Workbook and Calculus. The strongest association appears between Workbook and Calculus, as indicated by the tightly clustered points along the regression line, suggesting that workbook performance contributes substantially to calculus achievement.

While the multiple linear regression model quantifies the predictive contributions of Basic Math and Student Workbook to Calculus 1, it does not fully reveal the extent to which each predictor maintains a unique association with the outcome when the influence of the other variable is controlled. To address this, partial correlation analysis was employed. This approach enables the examination of the direct relationship between Basic Math and Calculus 1 after controlling for Student Workbook, and conversely, between Student Workbook and Calculus 1 after controlling for Basic Math. Such analysis provides a clearer understanding of the independent role each variable plays in shaping student achievement in calculus. These findings align with (Ranmechai & Poonputta, 2023), who reported that students' prior mathematical knowledge is a significant predictor of success in calculus, underscoring the essential role of basic mathematics in supporting achievement in higher-level mathematics courses.

Partial correlation analysis showed that Basic Math remained moderately associated with Calculus 1 after controlling for Student Workbook ($r = 0.58$, $p < 0.001$). However, the association between Workbook and Calculus 1 was stronger when controlling for Basic Math ($r = 0.75$, $p < 0.001$), indicating that while both factors are important, workbook engagement provides the greater unique contribution to calculus performance. This result is consistent with the findings of (Putra et al., 2024), who emphasized that scaffolded and structured learning materials, such as problem-based worksheets and workbooks, play a critical role in enhancing

students' conceptual understanding and improving performance in introductory university mathematics courses.

Limitation

This study is limited by its focus on a single cohort of first-year engineering students at one institution, which constrains the generalizability of the findings. The analysis also relied on short-term outcomes—exam performance and workbook engagement—without capturing longer-term learning or affective factors such as motivation and attitudes. In addition, possible instructor effects and prior familiarity with digital tools may have influenced the results. Future research should therefore involve larger and more diverse samples, longitudinal tracking, and broader measures of learning processes to strengthen and extend these conclusions.

Conclusion

This study investigated the implementation of a problem-based learning (PBL) approach supported by structured Student Workbooks and digital visualization tools in a first-year Calculus 1 course within the Telecommunication Engineering Program. The intervention aimed to address persistent challenges faced by students in mastering fundamental calculus concepts, often stemming from weak mathematical foundations and passive learning habits. The structured Student Workbook, *Modul Kalkulus 1*, was designed to provide progressive scaffolding through theoretical explanations, worked examples, visual representations, and problem-solving exercises aligned with Course Learning Outcomes (CLOs).

By analyzing the correlation between students' Student Workbook engagement and their performance in CLO-based assessments, the study demonstrated strong positive correlations across all CLOs ($r = 0.66\text{--}0.80$), with the most notable gains in CLO2 (Derivatives) and CLO4 (Applications of derivatives). This indicates that scaffolded practice and visualization are particularly powerful for topics requiring integration of symbolic rules with geometric and applied interpretations.

Furthermore, the use of digital visualization tools—alongside problem-based learning strategies—proved effective in enhancing conceptual understanding, particularly in abstract and multi-step calculus topics. The combination of PBL, scaffolding, and visual aids created an active learning environment that supported deeper engagement, critical thinking, and independent problem solving.

While these findings affirm the pedagogical value of structured Student Workbooks and visualization in engineering mathematics, the study is limited to a single program with a modest sample size. Future work should involve multi-institutional contexts, longitudinal tracking, and the application of this model to higher-level calculus or other STEM gateway courses.

Overall, the results support the integration of structured instructional Student Workbooks and visualization in teaching calculus, particularly in engineering education contexts. These tools not only bridge the gap between theory and application but also empower students to take greater ownership of their learning. In a broader sense, this work contributes to the growing body of evidence advocating for student-centred, technology-supported instruction in STEM higher education.

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