



STEM-integrated project-based learning: Students' critical thinking skills in trigonometry

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Abstract

Background: This study was motivated by the importance of critical thinking skill in solving problem and making the decision. In addition, low level of students' critical thinking skills issue in mathematics learning, particularly in trigonometry

Aims: To address this issue, a STEM-integrated Project-Based Learning (PjBL-STEM) model was implemented.

Method: This study employed a mixed-method approach combining quantitative and qualitative data. The sample consisted of 50 tenth-grade students at SMA Negeri Manufui, divided into an experimental class; 25 students and a control class; 25 students. Data were collected through a critical thinking skills test, student response questionnaires, and interviews.

Results: The results of the independent samples t-test showed a significant difference between the experimental and control classes (Sig. = 0.001 < 0.05). The mean posttest score of the experimental class (52.83) was higher than that of the control class (45.33). The N-Gain analysis indicated a low improvement category in both classes; however, the experimental class (26.29%) showed a higher increase compared to the control class (4.50%). Student responses toward the PjBL-STEM implementation were highly positive, with more than 90% agreement. Qualitative findings revealed that project-based experiences helped students recall concepts, identify reasoning errors, and reflect on problem-solving processes.

Conclusion: STEM-integrated PjBL model was effective in improving students' critical thinking skills and fostering active, collaborative, and meaningful learning. Continuous implementation supported by structured guidance and critical thinking exercises is recommended to achieve more optimal learning outcomes.

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INTRODUCTION

Education systems worldwide are increasingly required to cultivate learners who can reason critically within complex, technology-driven environments. International STEM agendas consistently position critical thinking as a core 21st-century competence necessary for interdisciplinary problem solving, analytical judgment, and evidence-based decision making (Klieger, 2026; Thornhill-Miller et al., 2023). In mathematics education, critical thinking is not an additional skill but a foundational element of meaningful understanding, as students must interpret representations, evaluate reasoning steps, and justify conclusions logically. However, despite curricular emphasis on higher-order thinking, classroom practice frequently remains procedural, prioritizing formula application and routine exercises over conceptual reasoning. This misalignment between intended competencies and instructional practice continues to constrain students' analytical development.

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Within this broader challenge, trigonometry represents a particularly demanding domain. Trigonometric reasoning requires students to coordinate symbolic manipulation, geometric visualization, proportional relationships, and contextual interpretation. Yet in many classrooms, trigonometry is presented as a set of isolated formulas rather than as a coherent system of relationships applicable to measurement and modeling situations. Empirical research has documented recurring misconceptions in trigonometric ratios, difficulties in connecting graphical and contextual representations, and limited ability to justify reasoning steps (Canonigo, 2025; Ferede et al., 2025). These patterns suggest that students' struggles extend beyond computational accuracy to weaknesses in core critical thinking processes such as problem identification, evaluation of assumptions, and formulation of coherent conclusions (Nussbaum, 2021).

To address these issues, recent scholarship has explored instructional models designed to promote deeper reasoning. Project-Based Learning has been widely recognized for engaging students in authentic problem contexts that require inquiry, collaboration, and reflection (Chang et al, 2024; Hussein, 2021; Williamson, 2023). Studies indicate that structured project phases can foster higher-order thinking by situating knowledge construction within meaningful tasks rather than isolated exercises. Similarly, STEM-integrated instruction has gained prominence for encouraging interdisciplinary connections among mathematics, science, technology, and engineering. Evidence across recent research suggests that STEM-oriented environments can enhance analytical reasoning and conceptual integration by linking abstract concepts to real-world applications (Le et al, 2023; Mystakidis et al., 2022). Within mathematics-specific contexts, research further emphasizes that critical thinking development is strengthened when students are required to justify arguments, evaluate solution strategies, and interpret multiple representations rather than execute routine procedures. Collectively, the state of the art supports the potential of combining project-based inquiry with STEM integration to foster higher-order thinking in mathematics.

However, closer examination reveals several unresolved issues. First, much of the existing literature concentrates on science education or broad mathematics achievement outcomes rather than focusing specifically on trigonometry at the senior high school level (Obeng et al., 2024; Owusu et al., 2023). Given the abstract and spatial characteristics of trigonometric reasoning, instructional effects observed in other mathematical domains cannot be assumed to transfer directly. Second, many prior studies rely predominantly on quantitative posttest comparisons. While such measures capture performance differences, they provide limited insight into whether observed gains reflect genuine development of reasoning processes or short-term procedural adaptation (van Loon & Laninga-Wijnen, 2025). Third, relatively few studies integrate students' reflective experiences, written reasoning patterns, and qualitative evidence into a unified analysis framework. As a result, the mechanisms through which STEM-integrated Project-Based Learning influences specific critical thinking indicators remain insufficiently explained.

These limitations indicate a substantive research gap (Neumann, 2021). Although previous research reports positive learning outcomes associated with Project-Based and STEM-oriented instruction, it remains theoretically and pedagogically unclear how STEM-integrated Project-Based Learning shapes critical thinking development within trigonometry at the senior high school level. In particular, the absence of mixed-method investigations restricts understanding of whether improvements in achievement scores correspond to deeper changes in reasoning behavior, such as error recognition, justification quality, and reflective conclusion drawing. Without integrating outcome-based evidence with analysis of students' reasoning processes, the instructional effectiveness of STEM-integrated Project-Based Learning in trigonometry cannot be fully established or theoretically grounded.

Addressing this gap is essential to clarify both effectiveness and mechanism. Therefore, this study aims to investigate the effect of STEM-integrated Project-Based Learning on students' critical

thinking skills in trigonometry at the senior high school level. In addition, the study examines students' responses and reasoning processes during project implementation through a mixed-method explanatory sequential design that combines quantitative analysis of learning outcomes with qualitative examination of students' written work and interview data.

The present study advances the literature in several significant ways. Theoretically, it refines understanding of how interdisciplinary project contexts activate specific indicators of mathematical critical thinking, including problem identification, reasoning justification, and reflective conclusion formulation within trigonometric tasks. Methodologically, it strengthens empirical rigor by integrating quantitative outcome comparison with qualitative process-oriented analysis, thereby addressing limitations of purely performance-based evaluation. Contextually, it provides focused evidence from senior high school trigonometry, a domain characterized by abstraction and persistent misconceptions that has received comparatively limited targeted investigation. Practically, the findings offer structured guidance for designing trigonometry instruction that promotes analytical depth, contextual modeling, and sustainable development of critical thinking in secondary mathematics classrooms.

METHOD

Research Design

This study adopted a mixed-method approach using an explanatory sequential design (Wipulanusat et al, 2020). The quantitative phase was conducted first to examine the effect of STEM-integrated Project-Based Learning on students' critical thinking skills. The subsequent qualitative phase was designed to explain and interpret the quantitative findings by exploring students' reasoning processes and learning experiences during project implementation. This design enabled a comprehensive evaluation of both outcome-based performance and process-oriented cognitive development. The study employed a nonequivalent control group design. The experimental group received instruction through STEM-integrated Project-Based Learning, while the control group was taught using conventional instructional methods. Both groups completed pretests and posttests to measure changes in critical thinking skills.

Participants

The research was conducted at Manufui State Senior High School during the even semester of the 2024/2025 academic year. The population consisted of all tenth-grade students enrolled in trigonometry. Two intact classes were selected using cluster random sampling. Class XD served as the experimental group and Class XC as the control group, each consisting of 25 students, resulting in a total of 50 participants.

Research Procedure

The intervention implemented in the experimental group followed a structured six-stage instructional sequence designed to integrate STEM principles with project-based inquiry. These stages are illustrated in Figure 1 and represent the operational framework of the treatment applied in this study. The procedure began with identifying learning objectives aligned with the trigonometry curriculum and explicitly connected to critical thinking indicators, including problem identification, evaluation of reasoning, justification of solutions, and formulation of conclusions. These objectives guided the design of all subsequent instructional activities. Next, project activities were designed to connect mathematical reasoning with real-world contexts. Students were assigned a project involving measurement of the height of objects such as trees or flagpoles using a clinometer application. This activity required students to collect data, apply trigonometric ratios, and interpret results within a contextual framework. During the project work phase, students collaborated in groups to gather measurements, construct representations, and solve contextual problems. The teacher acted as facilitator, providing scaffolding to ensure conceptual clarity and encouraging

analytical discussion rather than procedural execution. Students were then guided to explicitly engage in critical thinking processes. They analyzed collected data, examined the appropriateness of selected formulas, identified potential reasoning errors, and justified their solution strategies. This stage emphasized reflective reasoning as a central component of learning. Following project completion, students' critical thinking skills were assessed using a structured posttest aligned with predefined indicators. This stage generated quantitative evidence of learning improvement. Finally, students participated in reflective activities in which they reviewed their reasoning processes, discussed conceptual challenges, and identified errors encountered during the project. These reflections were documented and later analyzed qualitatively to interpret the quantitative findings.

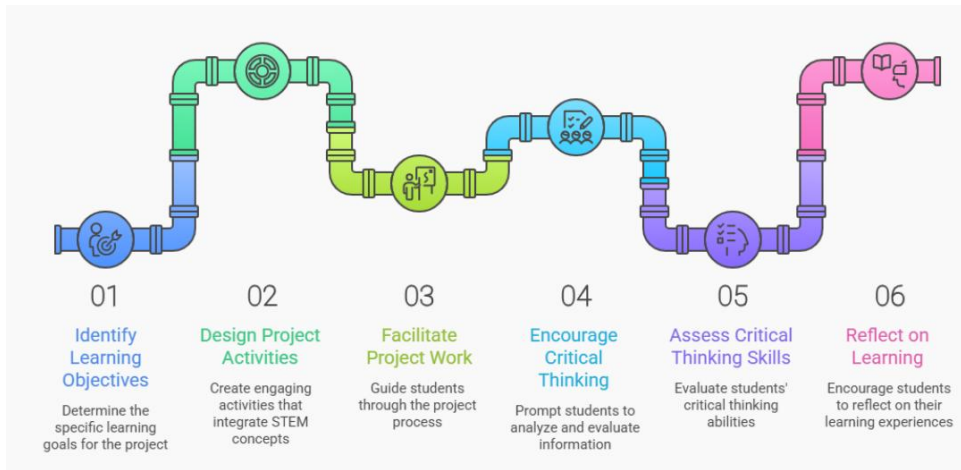


Figure 1. Instructional Stages of STEM-Integrated Project-Based Learning Implemented in the Experimental Group

Instruments

Two primary instruments were used in this study: a critical thinking skills test and a student response questionnaire. The critical thinking test was developed based on curriculum objectives and key indicators of mathematical critical thinking. Prior to implementation, the instrument was piloted in a separate class to evaluate its psychometric properties. Reliability testing using SPSS produced a Cronbach's Alpha coefficient of 0.856, indicating satisfactory internal consistency. Item validity was examined through Pearson correlation analysis, and all items demonstrated significant correlations at the 0.01 level, confirming their appropriateness for measuring critical thinking skills. The student response questionnaire was adapted from an established instrument and used to gather students' perceptions of the STEM-integrated Project-Based Learning experience. The questionnaire served as complementary qualitative support to interpret learning engagement and reflective processes.

Data Analysis

Quantitative data were analyzed using SPSS 25. Prior to hypothesis testing, normality and homogeneity tests were conducted to ensure statistical assumptions were satisfied. Differences between groups were examined using independent samples t-tests for normally distributed data. Within-group improvements were analyzed through paired comparisons, and learning gains were calculated using N-Gain analysis at a significance level of 0.05. Qualitative data derived from interviews and student reflections were analyzed using an interactive model consisting of data reduction, data display, and conclusion drawing. These qualitative findings were used to explain patterns observed in the quantitative results and to provide insight into students' reasoning development during the intervention.

RESULTS AND DISCUSSION

Results

Preliminary Analysis

To examine the effect of STEM-Integrated Project-Based Learning on students' critical thinking skills in trigonometry, prerequisite statistical tests were first conducted to ensure the appropriateness of parametric analysis. The results of the normality and homogeneity tests are presented in Table 1.

Table 1. Normality and Homogeneity Test Results

Test Type	Group / Variable	Sig. Value	Interpretation
Normality	Control - Pretest	0.074	Normally distributed
Normality	Control - Posttest	0.184	Normally distributed
Normality	Experimental - Pretest	0.115	Normally distributed
Normality	Experimental - Posttest	0.102	Normally distributed
Homogeneity (Levene's Test)	Pretest	0.109	Homogeneous variance

All significance values exceeded 0.05, indicating that the data were normally distributed and the variances between groups were homogeneous. These findings confirmed that parametric tests could be applied to examine differences in students' critical thinking performance in trigonometry.

Within-Group Improvement in Critical Thinking Skills

Following assumption testing, paired samples t-tests were conducted to determine whether students in each group experienced improvement in critical thinking skills from pretest to posttest. The results are summarized in Table 2.

Table 2. Paired Samples t-Test Results Within Groups

Group	Sig. (2-tailed)	Interpretation
Control Group	0.074	No significant improvement
Experimental Group	0.000	Significant improvement

The control group did not demonstrate a statistically significant improvement, suggesting that conventional instruction did not substantially enhance students' critical thinking skills in trigonometry. In contrast, the experimental group showed a statistically significant increase in posttest scores. This indicates that the implementation of STEM-Integrated Project-Based Learning was associated with measurable development of critical thinking abilities within the experimental group.

Between-Group Differences After the Intervention

To determine whether the instructional approach led to different levels of critical thinking performance between groups, an independent samples t-test was conducted using posttest scores. Descriptive statistics and significance values are presented in Table 3.

Table 3. Independent Samples t-Test and Posttest Descriptive Statistics

Group	N	Mean	Standard Deviation
Control Group	25	45.33	6.17
Experimental Group	25	52.83	8.04
Test	Sig. (2-tailed)	Interpretation	

The experimental group achieved a higher mean posttest score than the control group. The significance value of 0.001 indicates a statistically significant difference in critical thinking skills in trigonometry between students who experienced STEM-Integrated Project-Based Learning and those who received conventional instruction. This finding strengthens the evidence that the instructional intervention contributed to enhanced critical thinking performance.

Magnitude of Learning Improvement

To further evaluate the extent of improvement, N-Gain analysis was conducted for both groups. The results are presented in Table 4.

Table 4. N-Gain Descriptive Statistics

Group	Mean (%)	Minimum (%)	Maximum (%)	Standard Deviation	Category
Control Group	4.50	-27.27	29.41	15.47	Low / Ineffective
Experimental Group	26.29	0.00	55.56	13.86	Low / Ineffective

Although both groups were categorized within the low improvement range based on the established criteria, the experimental group demonstrated a substantially higher mean gain than the control group. This pattern suggests that STEM-Integrated Project-Based Learning produced greater relative improvement in students' critical thinking skills in trigonometry, even though overall effectiveness has not yet reached a moderate level.

Qualitative Insights into Critical Thinking Development

To complement the quantitative findings, qualitative data from students' written responses and interviews were analyzed to explore how critical thinking skills developed during the intervention. The analysis revealed that students in the experimental group demonstrated increased engagement in reasoning processes, including identifying relevant trigonometric relationships, evaluating solution strategies, and revising incorrect steps.

However, several challenges persisted. Some students misinterpreted contextual information, such as failing to decompose geometric representations accurately or neglecting unit consistency. Others selected inappropriate trigonometric ratios, particularly confusing sine and tangent functions. In certain cases, students produced numerical answers without articulating clear conceptual conclusions. These findings indicate that while STEM-Integrated Project-Based Learning enhanced analytical engagement, targeted scaffolding may still be required to strengthen conclusion formulation and representation linking in trigonometric reasoning. Overall, the qualitative findings support the quantitative results by demonstrating that students exposed to STEM-Integrated Project-Based Learning exhibited more active reasoning behaviors compared to those in the control group. The convergence of statistical and qualitative evidence provides a comprehensive picture of how the intervention influenced students' critical thinking skills in trigonometry.

Discussion

The results of this study demonstrate that the integration of STEM principles within a project-based framework can meaningfully influence students' critical thinking skills in trigonometry. The statistically significant improvement observed in the experimental group suggests that structured, contextual learning experiences create conditions that encourage analytical engagement (Karaoglan Yilmaz & Yilmaz, 2022). Rather than treating trigonometric ratios as isolated computational tools, students were required to interpret measurements, evaluate reasoning steps, and justify their conclusions. This shift from procedural execution to reflective reasoning appears to explain the difference between the two groups. In conventional instruction, students tended to rely on formula substitution without deeper conceptual processing (La Braca & Kalman, 2021). By contrast, the intervention required them to continuously connect abstract relationships with real-world contexts. Such demands likely stimulated more deliberate cognitive processing, which is central to critical thinking development.

The structured stages implemented during the intervention played a central role in shaping this outcome. Each stage, from defining learning objectives to engaging in reflective discussion, created repeated opportunities for students to examine their reasoning. In trigonometry, understanding the relationship between angle measures and proportional sides requires

coordination of symbolic and spatial thinking (Ubah, 2022). The project tasks, which involved measuring real objects and applying trigonometric ratios, required students to negotiate between representation and interpretation. This negotiation process may have supported the development of analytical awareness, as students were not merely solving problems but evaluating the appropriateness of their chosen methods Sun & Theussen (2023). Consequently, the improvement observed cannot be reduced to exposure to new material alone; it reflects a change in how students interacted with mathematical ideas.

Although the N-Gain results categorized overall improvement as low, this classification should be interpreted in context. The relatively short duration of the intervention may have limited the extent of measurable growth. Critical thinking skills are complex cognitive abilities that typically develop gradually through sustained engagement and repeated reflection (Bağ & Gürsoy, 2021; Culver et al, 2019). The difference in gain between the experimental and control groups, however, indicates that the instructional approach contributed to greater relative progress. Thus, while the numerical classification suggests modest improvement, the comparative evidence supports the instructional value of the intervention. Future implementations over longer periods may reveal stronger cumulative effects Diefenderfer et al. (2021).

The qualitative findings provide insight into how students' reasoning processes evolved during the learning experience. Students in the experimental group increasingly demonstrated awareness of reasoning errors, particularly during reflective discussions. Some initially misapplied trigonometric ratios or overlooked unit consistency, yet through collaborative evaluation they were able to recognize and correct these mistakes. This process of detecting and revising errors is a key feature of critical thinking (Umam & Susandi, 2022). However, not all indicators improved equally. Several students still struggled to articulate clear and logically structured conclusions, even when their numerical solutions were correct. This suggests that while analytical engagement improved, explicit emphasis on conclusion formulation may require further reinforcement Osakwe et al. (2024).

The interdisciplinary nature of the intervention also appears to have reduced the abstraction barrier commonly associated with trigonometry. By situating mathematical reasoning within measurement tasks and technological tools, students were required to translate physical observation into symbolic representation and back into contextual interpretation. This movement between concrete and abstract domains may have strengthened conceptual integration Borghi et al. (2022). In contrast, students in the control group often approached problems by identifying formulas first and interpreting meaning later, if at all. The difference in orientation highlights the potential of STEM integration to support representational flexibility, which is closely linked to higher-order thinking in mathematics Shvarts (2025).

Another important implication concerns the methodological contribution of combining quantitative and qualitative analysis. Statistical testing confirmed that the intervention produced significant differences in performance, yet numerical results alone would not reveal how students' reasoning actually changed. The qualitative evidence illustrates that improvement was reflected not only in score differences but also in more active evaluation of assumptions and increased willingness to revise incorrect reasoning. This convergence of findings strengthens the credibility of the conclusions. It also demonstrates that assessment of critical thinking in mathematics benefits from examining both outcomes and processes Romero Ariza et al. (2024). Integrating multiple forms of evidence allows for a more comprehensive understanding of instructional effectiveness (Imran & Almusharraf, 2024).

From a pedagogical standpoint, the findings underscore the importance of guided facilitation in project-based environments. The effectiveness of the intervention was not solely determined by the presence of projects but by the structured prompts that encouraged students to justify, evaluate, and reflect (Wijnia et al., 2024). Without such guidance, project activities risk becoming task-oriented

rather than reasoning-oriented. The results suggest that teacher scaffolding is essential to ensure that interdisciplinary tasks translate into cognitive engagement. Carefully designed questioning strategies and structured reflection sessions may therefore be crucial components of successful implementation (Marshall et al., 2022).

In summary, this study indicates that STEM-Integrated Project-Based Learning can support the development of students' critical thinking skills in trigonometry by fostering analytical engagement and representational coordination. While the overall magnitude of improvement remains moderate within the limited duration of the intervention, both quantitative and qualitative evidence point to meaningful shifts in reasoning behavior. The instructional approach appears particularly effective in promoting error recognition and conceptual linking, though additional emphasis on structured conclusion formulation may further strengthen outcomes. Taken together, the findings suggest that integrating contextual projects with explicit reasoning guidance offers a promising pathway for enhancing analytical depth in secondary mathematics classrooms (Zeynivandnezhad et al., 2024).

Implications

The evidence from this study suggests that STEM-Integrated Project-Based Learning can meaningfully support students' critical thinking skills in trigonometry by shifting learning away from routine substitution toward reasoning that requires interpretation, justification, and revision of ideas. When trigonometric concepts are embedded in project tasks that involve measurement and the use of tools, students are more likely to connect symbolic procedures with contextual meaning, which strengthens analytical engagement. The findings also indicate that project work alone is not sufficient, because gains are closely tied to how teachers structure guidance, prompt students to explain their choices, and lead reflection after problem solving. In addition, the mixed-method results show that critical thinking improvement is better captured when score changes are interpreted alongside students' written reasoning and interview responses, because this combination clarifies not only whether performance increased but also how students' reasoning developed in trigonometry learning.

Limitations

Several constraints should be considered when interpreting these results. The intervention was implemented within a limited time frame, which may have restricted the extent of measurable growth and contributed to the low N-Gain category even though statistical tests indicated meaningful differences between groups. The study also involved participants from a single school and a relatively small number of students, which means the findings may not automatically represent outcomes in other settings with different resources, student backgrounds, or instructional cultures. Although qualitative data helped explain the quantitative pattern, the qualitative scope remains limited because it did not include extensive observation of classroom interaction across all sessions, and deeper documentation might reveal additional factors that shaped how students engaged in critical thinking during project activities.

Suggestions

Future work should implement STEM-Integrated Project-Based Learning over longer instructional periods to examine whether sustained exposure produces stronger and more stable growth in critical thinking skills within trigonometry. Replication studies across different schools, larger samples, and varied classroom conditions are needed to test the consistency of the effect and identify context-sensitive factors that support or hinder implementation. Further refinement should also focus on targeted scaffolding for conclusion formulation and representation linking, because qualitative evidence indicates that some students still struggled to express coherent conclusions even when calculations were correct. Adding structured reasoning prompts, analytic rubrics, and

more systematic classroom observation could strengthen both instructional practice and research interpretation by capturing how students' reasoning evolves throughout project cycles.

CONCLUSION

This study explored how STEM-Integrated Project-Based Learning shapes students' critical thinking skills in trigonometry within a secondary school context. The findings show that students engaged in interdisciplinary project activities demonstrated stronger analytical performance than those who experienced conventional instruction. Learning tasks that required measurement, contextual interpretation, and collaborative reasoning encouraged students to examine assumptions, justify procedures, and reconsider incorrect steps rather than rely solely on formula substitution. Although the overall gain category remained modest, the consistent difference between groups and the qualitative evidence of improved reasoning behaviors indicate meaningful cognitive development. The results suggest that the value of the intervention lies not merely in score improvement but in changes in how students approach trigonometric problems. By situating abstract relationships within authentic contexts and structured reflection, the instructional model supported deeper engagement with mathematical ideas. However, the findings also imply that longer implementation periods and more focused scaffolding on conclusion formulation may further enhance critical thinking growth. Overall, this study provides empirical insight into how carefully designed, context-based mathematics instruction can foster more deliberate and reflective reasoning in trigonometry learning.

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AUTHOR CONTRIBUTIONS STATEMENT

Kristoforus Nofenaris Agung contributed to conceptualization, research design, data collection, data analysis, and drafting of the original manuscript. Meiva Marthaulina Lestari Siahaan contributed to supervision, methodological validation, critical review, and manuscript revision. Rika Handayani contributed to instrument validation, data interpretation, and manuscript review. Lailin Hijriani contributed to editing, proofreading, and final approval of the manuscript. All authors read and approved the final version of the manuscript.

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