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Integrating Scientific Inquiry in Mathematics Education: Development of a Problem-Based Learning Module to Enhance Mathematical Literacy in Vocational High School Students

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Abstract: This study aimed to develop a valid, practical, and effective Problem-Based Learning (PBL) mathematics teaching module integrated with scientific inquiry to enhance mathematical literacy among Grade X vocational high school students in a Computer and Network Engineering program. The development followed the Plomp model, comprising preliminary research, prototyping, and assessment phases. Data were collected through expert validation, student and teacher response questionnaires, observations, and pre- and post-tests. The module was validated by experts with an average score of 3.607 (very valid), while the student worksheets scored 3.582 (very valid). Practicality was confirmed with a 88.33% score from teachers and 88.40% from students, both categorized as very practical. The module significantly improved students' mathematical literacy, with an average post-test score of 82.66, reflecting gains in formulating, employing, and interpreting mathematical solutions within real-world vocational contexts. Findings indicate that the integration of scientific inquiry into PBL fosters deeper engagement and strengthens problem-solving skills.

Keywords: Mathematical Literacy; Module Development; Problem-Based Learning; Scientific Inquiry; Vocational Education

Introduction

In the evolving landscape of 21st-century education, mathematical literacy has emerged as a critical competency that enables individuals to analyze, reason, and communicate effectively when solving real-world problems using mathematics (Kain et al., 2024). For vocational high school (SMK) students in Indonesia, this skill is not only essential for academic success but also fundamental for navigating future workplace challenges that demand analytical thinking, problem-solving, and scientific reasoning (Kholifah et al., 2025). Despite its importance, empirical evidence and preliminary assessments—such as those conducted in this study at SMK Negeri 7 Batam—reveal that students' mathematical literacy remains unsatisfactorily low.

A key contributing factor is the persistent reliance on conventional, teacher-centered instructional models that prioritize procedural computation over contextual understanding and application (Cui et al., 2025). Moreover, teaching materials often lack integration with real-life or workplace-related contexts, particularly those aligned with students' vocational expertise, such as Computer and Network Engineering (TJKT) (Zhao & Ko, 2024). This gap limits students' ability to formulate, employ, and interpret mathematics in meaningful situations—an essential triad in the framework of mathematical literacy as defined by PISA (Marcq et al., 2024).

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The need for pedagogical innovation becomes even more urgent when considering the unique characteristics of vocational education (İlhan et al., 2025). Unlike general academic tracks, SMK curricula are designed to prepare students for direct entry into the workforce, where interdisciplinary competencies—especially the integration of science, technology, and mathematics—are increasingly demanded (Metreveli et al., 2025). However, current mathematics instruction in many SMKs remains disconnected from scientific inquiry and authentic technical problems, resulting in fragmented learning experiences (Ukobizaba et al., 2025).

As noted in prior research Xu et al. (2025), traditional teaching methods fail to engage students in deep cognitive processing, while contextualized learning models such as Problem-Based Learning (PBL) have demonstrated significant potential in improving mathematical literacy outcomes (Boom-Cárcamo et al., 2024). PBL encourages learners to investigate complex, open-ended problems, fostering self-directed learning, collaboration, and critical thinking—skills closely aligned with scientific inquiry processes (Song et al., 2025).

Scientific inquiry, as a pedagogical approach, emphasizes observation, questioning, hypothesis generation, data analysis, and evidence-based conclusion drawing—processes that mirror the stages of mathematical problem solving (Jong, 2023). When integrated into mathematics education, scientific inquiry transforms abstract concepts into dynamic investigations, enabling students to construct knowledge through exploration and reflection (Mesci et al., 2025). This synergy between science and mathematics is particularly relevant in vocational settings, where mathematical concepts such as sequences and series can be contextualized within network signal patterns, data transmission rates, or infrastructure cost calculations (Zuo et al., 2025). Yet, there remains a scarcity of instructional materials that systematically embed scientific inquiry within a PBL framework specifically tailored for SMK students (Sirisha et al., 2025).

This study addresses this gap by developing and evaluating a mathematics teaching module based on Problem-Based Learning integrated with scientific inquiry to enhance mathematical literacy among Grade X vocational high school students. Grounded in the principles of contextual learning and cognitive constructivism, the module is designed to guide students through authentic, occupation-relevant problems that require them to apply mathematical reasoning within a scientific investigation framework. For instance, students might explore how arithmetic sequences model the growth of network users over time or use statistical reasoning to evaluate system performance—tasks that not only reinforce mathematical concepts but also cultivate scientific habits of mind.

The development of this module is further informed by the Merdeka Curriculum (Independent Curriculum), which emphasizes student autonomy, character building, and real-world relevance in learning. By aligning the module with this national reform initiative, the study contributes to scalable and sustainable improvements in vocational mathematics education. Previous studies Kong et al. (2025), Kong & Zhu (2025), Kong et al. (2024) have shown that structured problem-solving frameworks significantly improve students' mathematical literacy; however, few have focused on the integration of scientific inquiry within PBL modules in vocational contexts. Thus, this research presents a novel contribution by merging three powerful educational dimensions: contextualized vocational content, problem-based learning, and scientific inquiry (Moundridou et al., 2024).

The primary objective of this study is to design, implement, and assess a valid, practical, and effective mathematics teaching module that enhances students' mathematical literacy through an integrated scientific-inquiry-based PBL approach. Specifically, it seeks to answer how such a module can support students in formulating real-world problems mathematically, employing appropriate strategies to solve them, and interpreting solutions in meaningful ways. The findings are expected to provide educators and curriculum developers with a replicable model for interdisciplinary instruction that bridges mathematics and science in vocational education. Furthermore, the module may serve as a reference for future development of context-specific teaching materials across other technical disciplines, ultimately supporting Indonesia's broader goals of improving STEM literacy and workforce readiness.

Method

This study employed a Research and Development (R&D) design based on the Plomp model, a systematic and iterative framework widely recognized for developing valid, practical, and effective educational products. The Plomp model consists of three distinct phases: (1) Preliminary Research, (2) Prototyping Phase, and (3) Assessment Phase. This structured approach ensured that the development of the Problem-Based Learning (PBL) module integrated with scientific inquiry was grounded in empirical data, theoretically informed, and responsive to the contextual needs of vocational high school (SMK) students (Kutscher, 2025).

In the Preliminary Research phase, a comprehensive needs analysis was conducted at SMK Negeri 7 Batam, focusing on Grade X students in the Computer and Network Engineering (TJKT) program. This phase involved four key analyses: (a) curriculum analysis to align the module with the Indonesian Independent Curriculum *(Kurikulum Merdeka)*, particularly the learning outcomes and scope of the sequences and series topic; (b) student characteristics analysis to understand cognitive levels, learning styles, and prior mathematical literacy skills; (c) concept analysis to identify core mathematical competencies and their real-world applications in networking and telecommunications; and (d) contextual needs analysis through interviews with mathematics teachers and preliminary observations. These data revealed critical gaps: low mathematical literacy performance, lack of contextualized teaching materials, and minimal integration of scientific inquiry in mathematics instruction.

The Prototyping Phase involved the design and iterative refinement of the instructional module. The initial prototype (Prototype 1) was developed based on the findings from the preliminary phase and grounded in PBL principles adapted from Barrows (1996) and scientific inquiry stages (observing, questioning, investigating, analyzing, and concluding). The module was structured around authentic, occupation-relevant problems—such as modeling network signal patterns using arithmetic sequences or calculating infrastructure costs using geometric series—thereby fostering interdisciplinary connections between mathematics and applied science. The core components of the module included: (1) Learning Outcomes aligned with the Merdeka Curriculum, (2) Learning Objectives, (3) scientific inquiry-based PBL activities, (4) student worksheets (Lembar Kerja Peserta Didik), (5) practice exercises with feedback, and (6) reflection sections to promote metacognitive awareness.

The prototype underwent three cycles of expert validation and empirical testing. First, content and construct validity were assessed by four validators: two mathematics education lecturers, one educational technology expert, and one language specialist. Validation instruments included structured checklists and scoring rubrics evaluating aspects such as scientific accuracy, alignment with PBL stages, linguistic clarity, visual design, and relevance to vocational contexts. Feedback from validators led to revisions, resulting in Prototype 2. Subsequently, one-to-one evaluation was conducted with three students of varying academic abilities to assess clarity, usability, and engagement. This was followed by a small group evaluation involving nine students, where think-aloud protocols, interviews, and observation checklists were used to identify practical challenges. Data from these evaluations informed further refinements, leading to Prototype 3.

In the Assessment Phase, the module's practicality and effectiveness were evaluated through a field test in a real classroom setting. A mathematics teacher implemented the module over several sessions with a class of Grade X TJKT students. Practicality was measured using: (a) teacher and student response questionnaires (on a Likert scale), (b) semi-structured interview guides, and (c) observation sheets assessing implementation feasibility, time efficiency, and student engagement. The questionnaire covered aspects such as ease of understanding, attractiveness, time efficiency, and perceived benefits of the module.

To evaluate effectiveness, a mathematical literacy test was administered as a pre-test and post-test. The test consisted of contextualized, open-ended problems aligned with PISA's mathematical literacy framework—assessing students' abilities to formulate, employ, and interpret mathematics in real-life and vocational scenarios. The test items were validated for content and construct validity and analyzed for reliability. Student responses were scored using a rubric adapted from the PISA proficiency levels, focusing on reasoning, problem-solving strategies, and interpretation of solutions.

Data were analyzed qualitatively and quantitatively. Qualitative data from interviews and open-ended questionnaire responses were thematically analyzed to capture insights on user experience and perceived learning benefits. Quantitative data from questionnaires and test scores were analyzed using descriptive statistics and paired-sample t-tests to determine significant improvements in mathematical literacy. This rigorous, multi-stage methodology ensured that the final product—named Prototype 5—was not only theoretically sound and contextually relevant but also empirically validated for validity, practicality, and effectiveness in enhancing mathematical literacy through a science-integrated PBL approach in vocational education.

Result and Discussion

The development of the Problem-Based Learning (PBL) module integrated with scientific inquiry resulted in a high-quality, contextually relevant instructional product designed to enhance mathematical literacy among Grade X vocational high school students in the Computer and Network Engineering (TJKT) program. The results are presented according to three core criteria: validity, practicality, and effectiveness, supported by tables, observations, and visual representations derived from expert validation, field testing, and student performance data.

Validity of the Module and Student Worksheets

The module and accompanying Student Worksheets *(Lembar Kerja Peserta Didik/LKPD)* were evaluated by four experts in mathematics education, educational technology, and linguistics. The assessment covered four aspects: content, didactic, visual design, and language. The results are summarized in the Tables 1.

Table 1. Validity Assessment of the Mathematics Teaching Module

Aspect	Average Score	Category
Content	3.60	Very Valid
Didactic	3.50	Very Valid
Visual Design	3.70	Very Valid
Language	3.63	Very Valid
Overall	3.607	Very Valid

Table 2. Validity Assessment of the Student Worksheets (LKPD)

Aspect	Average Score	Category
Content	3.50	Very Valid
Didactic	3.33	Valid
Visual Design	3.50	Very Valid
Language	4.00	Very Valid
Overall	3.582	Very Valid

These results confirm that both the module and LKPD met the required standards for use in classroom instruction, with high scores across all validation criteria. Experts particularly praised the integration of real-world vocational contexts, alignment with the Merdeka Curriculum, and clarity of scientific inquiry stages embedded in the PBL framework.

Practicality of the Module

The practicality of the module was assessed through one-to-one evaluation, small group trials, and field testing using teacher and student response questionnaires. The results are presented below.

Table 3. Practicality Assessment Results

Component	Practicality Score (%)	Category
Teaching Module	88.33	Very Practical
Student Worksheets (LKPD)	83.52	Practical

Students reported that the module was easy to understand, visually engaging, and effectively guided them through problem-solving stages. Teachers noted that the module was time-efficient and easy to implement, with clear instructions and well-structured activities.

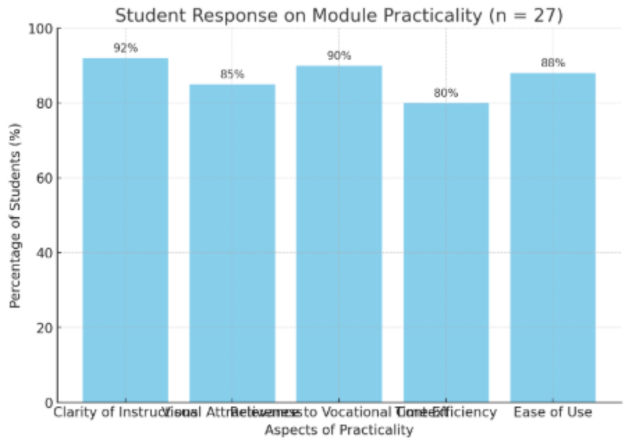

Figure 1. Student Response on Module Practicality (n = 27)

The integration of visual elements—such as images of students in SMK uniforms discussing network problems with laptops and cables (see Figure 2)—was highlighted as a key factor in increasing engagement. The cover design, featuring patterned numbers (2, 4, 6, 8) symbolizing sequences and series, reinforced the mathematical theme and vocational relevance.

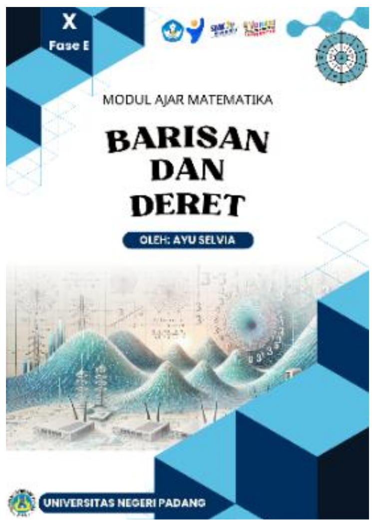

Figure 2. Final Cover Design of the Student Worksheets

This design was revised after expert feedback to improve color harmony, layout, and visual clarity, resulting in a more professional and motivating appearance.

Effectiveness in Enhancing Mathematical Literacy

The module's effectiveness was measured using a pre-test and post-test design aligned with PISA's mathematical literacy framework, assessing three key indicators: formulate, employ, and interpret.

Table 4. Pre-test and Post-test Average Scores (n = 27)

Indicator	Pre-Test Average	Post-Test Average	Gain
Formulate	58.2	78.6	+20.4
Employ	55.4	84.1	+28.7
Interpret	52.7	85.3	+32.6
Overall	55.4	82.66	+27.26

The significant improvement in scores—especially in the interpret phase—demonstrates that students became more capable of connecting mathematical solutions to real-world contexts, such as calculating network infrastructure costs or analyzing signal growth patterns using arithmetic and geometric sequences.

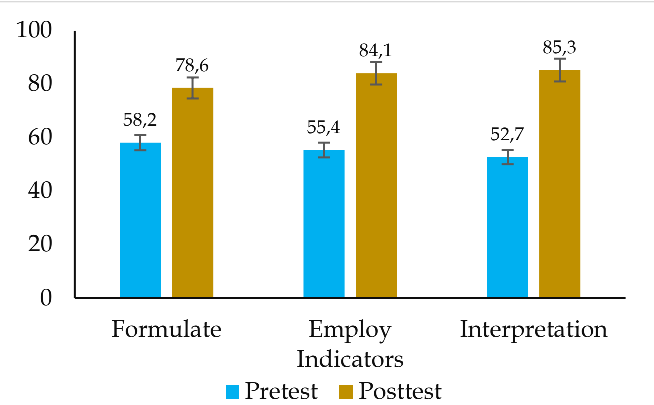

Figure 3. Pre-test vs. Post-test Performance

A paired sample t-test confirmed that the difference between pre- and post-test scores was statistically significant ($p < 0.05$), indicating that the module had a substantial positive impact on students' mathematical literacy.

Observational Evidence of PBL and Scientific Inquiry Stages

Classroom observations confirmed that students actively engaged in all five stages of PBL, which were aligned with scientific inquiry processes: orientation to the Problem – Students identified real-world issues (e.g., optimizing cable usage in network installation); organizing Learning – Groups formulated mathematical models (e.g., arithmetic sequences for cost prediction); guided Investigation – Students collected data, applied formulas, and solved problems collaboratively; developing and Presenting Results – Solutions were presented using logical reasoning and visual aids; and analyzing and Evaluating – Reflection sessions helped students interpret results and assess solution validity.

These stages fostered not only mathematical literacy but also scientific habits of mind—such as questioning, analyzing data, and drawing evidence-based conclusions.

The findings of this study provide strong empirical evidence that the integration of scientific inquiry within a Problem-Based Learning (PBL) framework significantly enhances mathematical literacy among Grade X vocational high school students (Pimdee et al., 2024). The developed module was validated as very valid, assessed as very practical, and proven effective, with students demonstrating substantial improvements in all three core indicators of mathematical literacy: formulate, employ, and interpret. These results are not only consistent with established educational theories but also contribute meaningfully to the growing body of research on context-based and interdisciplinary mathematics instruction.

The significant improvement in students' mathematical literacy—particularly in the interpret indicator, which showed the highest gain—suggests that the scientific inquiry-based PBL approach successfully guided learners beyond mere procedural competence toward deeper conceptual understanding and real-world application. The structured PBL stages, aligned with scientific inquiry (observing, questioning, investigating, analyzing, and concluding), encouraged students to actively engage with authentic vocational problems, such as calculating network cable distribution or analyzing signal strength decay using geometric sequences. This process enabled students to formulate real-life situations into mathematical models, employ appropriate mathematical tools, and critically interpret their solutions within the problem context.

Notably, classroom observations revealed that even when errors occurred—such as incorrect use of inequality signs or miscalculations—students were often able to self-correct through group discussion and teacher feedback. This reflects the development of metacognitive skills and collaborative reasoning, which are central to both PBL and scientific inquiry. The final average post-test score of 82.66 confirms that the module effectively supported students in achieving a good level of mathematical literacy, surpassing baseline performance observed in pre-test data.

The success of the module aligns closely with constructivist learning theory, which posits that learners construct knowledge through active engagement and reflection on meaningful experiences (Vygotsky, 1978; Bruner, 1966). By embedding mathematics within realistic, occupation-relevant scenarios, the module facilitated contextual learning, allowing students to connect abstract concepts with tangible applications—an essential component of vocational education (Schoute et al., 2024).

Furthermore, the results support the theoretical synergy between PBL and scientific inquiry, as both emphasize problem orientation, student autonomy, and evidence-based reasoning. This integration echoes the work of Barrows (1996), who emphasized that PBL fosters higher-order thinking by immersing learners in ill-structured, real-world problems. Similarly, the enhancement of the interpret indicator resonates with the final stage of PBL—analyzing and evaluating the problem-solving process—which directly corresponds to the interpret domain in PISA's mathematical literacy framework (Marcq et al., 2024).

These findings are also consistent with prior empirical studies. For instance, that PBL significantly improves mathematical literacy among SMK students compared to conventional instruction, particularly when students' self-confidence is nurtured through collaborative learning. In this study, the positive student responses and high practicality scores suggest that the module not only enhanced cognitive skills but also boosted motivation and engagement—key factors in fostering self-efficacy (Rendón-Castrillón et al., 2023).

Additionally, Bulut Ates & Aktamis (2024) developed a PBL-based Student Worksheet (LKPD) and concluded that such tools are highly feasible and effective in facilitating mathematical literacy. The current study extends this finding by integrating scientific inquiry and aligning the module with vocational contexts, thereby enhancing its relevance and applicability in technical education.

This study offers significant implications for education practice, curriculum development, policy, and future research. For teachers and practitioners, the developed module provides a ready-to-use, contextually grounded instructional tool that facilitates student-centered and inquiry-based learning in mathematics classrooms. By embedding problem-solving within authentic vocational scenarios—such as calculating network cable costs or analyzing signal patterns using arithmetic and geometric sequences—the module exemplifies how STEM integration can be realized in technical education, particularly by linking scientific inquiry with mathematical reasoning.

For curriculum developers, the successful alignment of the module with the Indonesian Merdeka Curriculum underscores the potential of innovative teaching materials to support national educational reforms that prioritize learner autonomy, critical thinking, and real-world application. The findings also carry important policy implications, advocating for the broader implementation of interdisciplinary, problem-based learning resources in vocational education to better bridge the gap between academic knowledge and workplace competencies.

Furthermore, this research establishes a replicable model for developing context-specific instructional modules, offering a valuable framework for future researchers aiming to enhance teaching and learning across various subjects and vocational fields. Despite these contributions, several limitations must be acknowledged. The module was designed and tested exclusively on the topic of Sequences and Series, which limits its generalizability to other mathematical domains. The field testing was confined to a single vocational program—Computer and Network Engineering—at SMK Negeri 7 Batam, potentially affecting the external validity of the results. Additionally, the evaluation of effectiveness relied on short-term assessments through pre- and post-tests, without longitudinal data to determine knowledge retention or skill transfer over time.

Moreover, while the module demonstrated high practicality, its implementation was closely supported by the researcher, which may not fully represent typical classroom conditions where teachers independently deliver instruction. To extend this work, future research should expand the module's scope to other mathematics topics such as functions, statistics, or trigonometry, and adapt them to different vocational disciplines. Multi-site studies across diverse SMKs and regions are recommended to evaluate the module's scalability and adaptability in varied educational contexts.

Longitudinal studies should be conducted to assess the sustained impact of the module on students' mathematical literacy and career readiness. Furthermore, integrating digital technologies—such as mobile-based applications, augmented reality, or blended learning platforms—could enhance engagement and accessibility. Finally, future studies should explore affective factors such as students' self-confidence, motivation, and attitudes toward mathematics and science, building on prior evidence that Problem-Based Learning positively influences both cognitive and non-cognitive outcomes.

Conclusion

This study developed a Problem-Based Learning (PBL) mathematics module integrated with scientific inquiry to improve mathematical literacy among Grade X vocational high school students. The module, focused on the topic of sequences and series and contextualized within computer and network engineering, was designed following the Plomp model and validated by experts, achieving high scores for validity, practicality, and effectiveness. Results showed a significant improvement in students' mathematical literacy, with an average post-test score of 82.66, particularly in formulating, employing, and interpreting mathematical solutions in real-world vocational contexts. The findings confirm that the integration of PBL and scientific inquiry enhances student engagement, problem-solving skills, and conceptual understanding, providing a practical and effective instructional tool for vocational mathematics education.

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