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Teachers' Didactical Challenges in Implementing Technology Integrated Project-Based Learning in Mathematics

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ABSTRACT

This study examines the didactic challenges experienced by mathematics teachers in implementing technology-integrated Project-Based Learning (PjBL) in North Sumatra, Indonesia. Previous studies have focused mainly on student outcomes, while limited attention has been given to teachers' didactic work in managing projects, technology, and mathematical understanding simultaneously. This study aims to analyze how teachers interpret and negotiate these challenges so that technology supports mathematical reasoning rather than functioning only as instructional media. A qualitative phenomenological design was employed involving 22 high school mathematics teachers selected through purposive criterion sampling. Data were collected through open-ended interviews and analyzed using phenomenological thematic analysis assisted by NVivo. The findings identified six major themes: tensions between project activities and conceptual depth, technology as a didactic black box, classroom management complexity, challenges in statistical reasoning, assessment dilemmas, and reflective didactic work. Teachers used technologies such as GeoGebra, Canva, Excel, Google Classroom, and Quizizz, yet most served primarily as presentation tools rather than as cognitive tools for mathematical thinking. The study contributes to theory by proposing a pentagonal didactical structure comprising teacher, student, mathematics, technological artifact, and project.

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1. INTRODUCTION

Mathematics learning in the 21st century requires students not only to master procedural fluency but also to model, reason, and make decisions in meaningful, real-world contexts. Within this framework, Project-Based Learning (PjBL) has gained increasing attention as a pedagogical model centered on authentic problems, sustained inquiry, collaboration, and the production of accountable artifacts. Various studies confirm that PjBL has the potential to improve conceptual understanding, learning engagement, problem-solving skills, and the quality of mathematics and statistics learning experiences [1], [2], [3], [4]. Experiential learning prepares students for real-life challenges by integrating knowledge with practice, thereby enhancing their readiness for professional roles [5]. Krajcik and Shin define PjBL as a learning method in which students acquire knowledge and skills by working over an extended period to investigate and respond to complex, authentic, and engaging questions, problems, or challenges [6]. This learning approach is increasingly relevant in mathematics education because it allows students to connect abstract mathematical concepts to contextual situations through investigation, modeling, and collaborative problem-solving. However, the success of PjBL does not lie in the existence of the project itself, but rather in the quality of the design, suitability to learning objectives, and the teacher's ability to ensure that project activities continue to lead to mathematical understanding. This condition indicates that teachers' didactical competence strongly influences the effectiveness of PjBL in designing and managing meaningful learning situations.

Technology integration further expands the possibilities for implementing PjBL in mathematics. Technology can provide space for information exploration, simulation, visualization, data modeling, synchronous and asynchronous collaboration, and communication of project results. Smaldino, Lowther, and Mims describe instructional technology as any medium teachers use purposefully to support student learning outcomes, ranging from traditional tools to sophisticated digital systems [7]. Furthermore, Mayer, in his Cognitive Theory of Multimedia Learning, asserts that people learn more deeply when ideas are presented through words and images rather than words alone, suggesting that technology-mediated representations can deepen mathematical understanding when appropriately designed [8]. Technology in mathematics learning, therefore, functions not merely as instructional media but also as a cognitive tool that supports reasoning, visualization, and mathematical communication. However, technology does not work optimally automatically. Its presence alters the relationships among teachers, students, mathematics, and learning artifacts. In the digital era and with the rise of artificial intelligence, the role of teachers is increasingly important as mediators who organize the use of artifacts so that learning remains didactically productive [9], [10].

Empirical findings on technology-integrated PjBL in mathematics illustrate a complex reality. Several studies report improvements in understanding statistical concepts, statistical literacy, collaborative skills, and creative confidence [11], [12]. However, these benefits are often accompanied by serious implementation challenges, including high time requirements, cognitive load, difficulty selecting relevant project topics, complex group dynamics, student anxiety towards open-ended tasks, and assessment challenges [13], [14]. These findings demonstrate that positive student outcomes do not automatically guarantee that the learning process is didactically effective. Teachers remain responsible for maintaining the balance between project activities, technology integration, and mathematical substance. In other words, seemingly positive learning outcomes do not automatically explain how teachers manage the didactic complexities underlying PjBL implementation itself.

The research question, therefore, shifts from the question of "is PjBL effective" to a more fundamental one: how do mathematics teachers didactically enable technology-integrated PjBL to work in real classrooms? Ball, Thames, and Phelps assert that teachers require content knowledge for teaching that goes beyond ordinary material mastery, including specialized content knowledge, knowledge of content and students, and knowledge of content and teaching [15]. In PjBL, these demands are increasingly complex because teachers must simultaneously design projects, anticipate student responses, orchestrate the use of technology, and maintain the mathematical substance of project activities. This complexity poses a major challenge for mathematics teachers, as technology-integrated PjBL requires the simultaneous integration of pedagogical, technological, and mathematical knowledge.

The didactic framework suggests that teachers' challenges cannot be reduced to technical implementation issues. Didactic Situation Theory and didactical engineering emphasize the importance of epistemological analysis, milieu, didactic contract, didactic variables, and the mediating role of teachers in designing productive learning situations [16], [17]. Straesser warns that when mathematics is mediated by technology, there is a risk of mathematics being hidden behind procedural and digital black boxes [18]. Said, Mansour, and Abu-Tineh empirically demonstrated that STEM teachers who implement PjBL with technology integration face particular challenges in aligning with TPACK, with preparatory school teachers showing greater variability than secondary school teachers [19]. Mansour, Said, and Abu-Tineh further found that teachers' TPACK competencies and self-efficacy for PjBL and STEM are significantly influenced by institutional support, training opportunities, and the nature of professional development received [20]. These studies indicate that successful technology-integrated PjBL implementation requires not only technological facilities, but also strong didactical preparation, professional support, and teachers' reflective capacity in managing mathematical learning situations.

Previous studies have largely emphasized student outcomes. The specific didactic challenges of mathematics teachers in designing, managing, and evaluating technology-integrated PjBL remain underexplored. Putra et al. showed that even in the context of teacher education, prospective teachers' reflections on the pedagogical functions of technological tools in PjBL contexts remain underdeveloped, suggesting a systematic gap in didactic preparation for technology-integrated project work [21]. Most previous studies also focused on measuring learning achievement, motivation, or technological effectiveness, while paying limited attention to how teachers interpret and negotiate didactical challenges during implementation. This condition creates a research gap regarding teachers' didactical work as the core element in technology-integrated mathematics learning. This article, therefore, focuses on analyzing teachers' didactic challenges in implementing technology-integrated PjBL in mathematics. The novelty of this research lies in shifting the focus from the dominant study of impacts on students to teachers' didactic work as the center of implementation. This study is expected to contribute theoretically by strengthening discussions on didactical work in technology-mediated mathematics learning and practically by providing insights for teacher professional development, instructional design, and the implementation of meaningful technology-integrated PjBL in mathematics classrooms.

This study aims to understand the experiences of mathematics teachers in North Sumatra in facing didactic challenges when implementing technology-integrated PjBL. Two research questions guide this study: (1) How do mathematics teachers in North Sumatra experience didactic challenges when implementing technology-integrated PjBL so that technology not only functions as a technical tool but also supports students' mathematical thinking processes? Furthermore, (2) How do teachers interpret these didactic challenges in the process of designing, implementing, and evaluating mathematics learning in technology-integrated PjBL? Through this focus, the study seeks to provide a deeper understanding of how teachers mediate relationships among technology, mathematical thinking, project activities, and classroom interactions in contemporary mathematics learning environments.

2. METHOD

This study uses a qualitative approach with a phenomenological design. The choice of this design is based on the research objective: to deeply understand the lived experiences of mathematics teachers when facing didactic challenges in implementing technology-integrated PjBL in mathematics learning. This study does not merely inventory technical obstacles but examines how teachers experience, interpret, and give meaning to didactic challenges in learning practices. The phenomenological design is considered most appropriate because it focuses on participants' shared experiences with a phenomenon, then describes and interprets those experiences until the essence of the phenomenon is obtained. This position aligns with Creswell and Creswell's description of phenomenology as a design for describing the lived experiences of participants with a phenomenon [22]. The phenomenological approach also allows researchers to explore the relationship between teachers' pedagogical decisions, technology use, and the didactical meanings constructed during mathematics learning practices.

The research participants were 22 mathematics teachers in North Sumatra who had experience implementing technology-integrated PjBL. The selection of participants was carried out using purposive criterion sampling. The criteria included: (1) active mathematics teachers in high schools in North Sumatra; (2) minimum three years of teaching experience; (3) having implemented technology-integrated PjBL at least twice in the last two years; and (4) being willing to provide written, reflective answers about their teaching experiences. The participants came from different school contexts, including urban and semi-urban schools, to obtain more varied perspectives regarding the implementation of technology-integrated PjBL in mathematics classrooms. This sampling strategy was intended to ensure that participants possessed adequate experiential knowledge relevant to the phenomenon under investigation.

The research instrument consisted of open-ended interviews compiled in a Google Form and distributed to participants. The researcher remained the primary instrument, serving as a medium for collecting participants' narratives of experience. The interview questions were structured in two sections: demographic and professional information, and substantive open-ended questions that explored teachers' experiences in designing projects, selecting technology, managing student activities and responses, maintaining project linkages to mathematical objectives, addressing misconceptions, and assessing student learning processes and outcomes. Prior to use, the instrument was reviewed by experts in mathematics education and research methodology to assess its clarity, directionality, and suitability to the phenomenon under study [23], [24]. The use of written open-ended interviews allowed participants to provide reflective, detailed responses about their teaching experiences, though the researchers acknowledged that this format might limit opportunities for direct probing during data collection.

Ethical procedures were implemented throughout the research process. Participants were informed of the study's purpose, the voluntary nature of their participation, and the confidentiality of their identities and responses before completing the interview form. Informed consent was obtained electronically through the Google Form prior to data collection.

Data were analyzed through phenomenological thematic analysis using NVivo. The analysis process began by repeatedly reading all participant responses to gain a comprehensive understanding. Next, the researcher marked significant statements related to didactic challenges, assigned initial codes, grouped the codes into main themes, and formulated descriptions of what teachers experienced and how they interpreted it, until the essence of the phenomenon was obtained. The coding process involved horizontalization, identification of meaning units, thematic categorization, and the development of textural and structural descriptions to interpret the essence of teachers' experiences. This approach aligns with phenomenological procedures that emphasize identifying significant statements and formulating the essence of experience [25]. To ensure trustworthiness, the study applied credibility, dependability, and confirmability procedures through expert review, systematic coding and documentation, and repeated examination of participant responses during analysis. Member checking was also conducted by confirming several interpreted findings with participants to ensure consistency in the meanings and interpretations produced by the researchers.

3. RESULTS AND DISCUSSION

This study involved 22 high school mathematics teachers from various regions in North Sumatra, including Medan, Deli Serdang, Langkat, Kisaran, Simalungun, Binjai, and Padang Lawas. Their teaching experience varied: 5 teachers had 0–10 years, 12 had 11–20 years, and 5 had more than 20 years. In terms of qualifications, 18 teachers held bachelor's degrees and 4 teachers held master's degrees. Participants also represented diverse school contexts, including urban, suburban, and rural schools, providing broader perspectives on the implementation of technology-integrated PjBL across different educational settings.

3.1. Results

The analysis was conducted using NVivo through the stages of horizonalization, meaning units, clustering of meanings, and the formation of textural-structural descriptions. The coding process was conducted systematically by identifying significant statements, assigning initial open codes, grouping similar codes into categories, and synthesizing them into thematic structures through iterative comparison across participants' narratives. The initial coding produced 148 open codes that were condensed into 18 sub-themes through

1

axial coding. Through iterative reading, the sub-themes were grouped into six main themes: (T1) didactic tension between project activities and depth of mathematical concepts; (T2) technology as a didactic black box; (T3) the complexity of classroom management and didactic differentiation; (T4) didactic challenges specific to statistics; (T5) the assessment dilemma between group products and individual understanding; and (T6) teachers' reflective didactic work. Although frequency counts were used to indicate thematic prominence, the interpretation remained focused on understanding the essence and meaning of teachers' lived experiences rather than quantification alone. The richness of references for each theme is shown in Table 1. 24

Table 1. Themes, sub-themes, and frequency of references from NVivo analysis results

Main Theme	Sub-Theme	Freq.	Participants
T1. Project tension–concept	Projects are more dominant than mathematical concepts	19	R1,R3,R4,R6-R22
	Difficulties of mathematical modeling	13	R2,R3,R6,R8-R12,R15-R17,R20,R21
	Time management vs depth of concept	11	R3,R7-R10,R14,R15,R17,R19-R21
T2. Technology as a black box	Technology is used cosmetically, not cognitively	15	R1,R3,R4,R7,R9,R11,R12,R14-R17,R19-R22
	Reliance on AI and instant results	9	R5,R9,R14,R16-R18,R20-R22
	Access and infrastructure gaps	6	R10,R11,R13,R19,R20,R22
T3. Complexity of classroom management	Group dynamics and free-riders	12	R1,R3,R7-R9,R11,R14,R15,R17,R18,R20,R21
	Heterogeneity of student abilities	10	R4,R6,R8,R10,R11,R13-R15,R17,R20
	Shifting roles of teachers	7	R2,R3,R9,R14,R16,R17,R20
T4. Statistical challenges	Data interpretation and drawing conclusions	16	R1,R3,R6-R8,R10-R17,R19-R21
	Misconceptions about measures of central tendency and variability	14	R1,R4,R5,R7,R8,R10-R12,R14-R17,R20,R21
	Correlation vs. causality	6	R9,R13,R15,R16,R18,R22
	Selection of appropriate data/context	12	R1,R3-R5,R7,R8,R10,R12,R14,R15,R17,R21
T5. Project assessment dilemma	It is difficult to separate individual understanding from group products.	14	R3,R4,R6-R10,R12,R14-R17,R20,R21
	Process vs. end product assessment	9	R4,R6,R8,R11,R14,R16,R18,R19,R21

Main Theme	Sub-Theme	Freq.	Participants
T6. Reflective didactic work	Phased scaffolding and checkpoints concept	13	R2,R3,R6,R8-R10,R12,R14,R16,R17,R20-R22
	Post-project reflection and debriefing	8	R3,R4,R8,R9,R11,R14,R17,R22
	Backward design and concept orientation	7	R3,R8,R12,R14,R16,R17,R20

3.1.1 Theme 1: Didactic Tensions between Project Activities and Mathematical Concept Depth

The first theme emerged most dominantly, with 43 references from all 22 participants. Teachers consistently described their experiences as a tug-of-war between two poles: project activities that demand collaborative products and processes, and the depth of understanding of mathematical concepts that is an essential goal of learning. R3 reflected on this:

> *"The main challenge is not just making the project interesting, but keeping it truly teaching math concepts, not just a fun activity." (R3)*

R6 emphasized that the main difficulty in designing project-based learning is maintaining a balance between project activities and the depth of understanding of mathematical concepts. R14 articulated this tension in the form of the backward design principle:

> *"I design projects using the principle of backward design. I first set the goal of understanding the concept, then determine which project product best demonstrates that understanding." (R14)*

This tension manifested most sharply during the mathematical modeling phase. Thirteen participants explicitly identified mathematical modeling as the most difficult concept to present within the project framework. R9 described this phenomenon with keen epistemological awareness:

> *" Real-world problems can actually be solved with simple logic or basic arithmetic. However, due to curriculum demands, we as teachers sometimes design projects that seem to require these formulas." (R9)*

Statement R9 reveals a typical didactic paradox: the desire to present authentic projects can clash with the need to instill higher-order mathematical concepts. Krajcik and Shin assert that effective PjBL requires a scientifically sound and pedagogically coherent 'driving question', meaning that authenticity alone is insufficient without conceptual alignment [6]. Teachers developed three main strategies: (a) establishing a conceptual goal as the leading objective; (b) inserting concept checkpoints at each stage of the project; and (c) weighting the assessment rubric that places conceptual understanding above the aesthetics of the product. R21 articulated a rubric with 70% for conceptual accuracy, 20% for process, and 10% for neatness.

3.1.2 Theme 2: Technology as a Didactic Black Box

The second theme emerged with 30 references, including codes related to cosmetic technology use, reliance on AI, and access or infrastructure gaps. Contrary to assumptions that teachers underutilize technology, all 22 participants actively used digital tools in mathematics PjBL learning.

The technologies reported included GeoGebra, Canva, Microsoft Excel, Google Sheets, PowerPoint, Google Forms, Google Classroom, Quizizz, Kahoot, YouTube, and artificial intelligence platforms such as ChatGPT and Grok. GeoGebra was primarily used for visualization and graph exploration, while Excel and Google Sheets supported statistical analysis and data representation. Canva and PowerPoint were primarily used for project presentations and reporting.

Table 2. Technology integration patterns in each PjBL phase based on research findings

PjBL Phase	Reported Technology	Usage Categories	Intensity
Phase 1: Determining Guiding Questions	YouTube (3 teachers)	Introductory media, contextual motivation	Low
Phase 2: Project Planning	Google Forms, Google Classroom (4-5 teachers)	Distribution of worksheets and initial assignments	Currently
Phase 3: Scheduling	Google Classroom (4 teachers)	Deadline reminder	Low
Phase 4: Implementation and Data Processing	GeoGebra, Excel, Google Sheets, AI (8-10 teachers)	Data visualization, processing, and analysis	Tall
Phase 5: Presentation of Results	Canva, PowerPoint, GeoGebra (9-10 teachers)	Presentation media and project reports	Tall
Phase 6: Evaluation	Quizizz, Kahoot, Google Forms (4-5 teachers)	Formative and summative assessment	Currently

Despite the wide range of technologies used, thematic analysis revealed a pattern that poses a major didactic issue: most technologies functioned solely as learning media in specific phases, rather than as integrated cognitive tools across all six phases of PjBL. GeoGebra, for example, was predominantly used in the data processing phase to visualize shapes and graphs, while its potential as an interactive exploration tool in the guiding questions or project planning phases was rarely utilized. Canva and PowerPoint were used almost exclusively in the results presentation phase. Quizizz and Kahoot were used in the evaluation phase. Google Classroom primarily served as an assignment submission platform rather than as a space for ongoing mathematical collaboration and reflection.

Smaldino, Lowther, and Mims warn that instructional technology that is not pedagogically aligned with learning outcomes will stop at the substitution level and fail to modify or redefine learning tasks. Mishra and Koehler emphasize that meaningful technology integration requires Technological Pedagogical Content Knowledge (TPACK) that simultaneously interconnects content knowledge, pedagogy, and technology, rather than treating them separately [26]. When teachers use GeoGebra only to visualize the final result without utilizing its interactive features for early concept exploration, or use Excel only to create graphs without encouraging students to interpret data patterns, then the technology functions only as a presentation medium, not a mediator of mathematical thinking.

Teachers consistently experience technology as a double-edged sword: it opens up possibilities for data visualization and analysis, but also hides the mathematical structures that students are supposed to learn. Smaldino et al. caution that technology should always serve as a means to enhance learning outcomes, not as an end in itself. When technology is used without a clear pedagogical purpose, it becomes what R14 calls the cosmetic use of technology:

" Avoid using technology that is merely cosmetic or merely a substitute." (R14)

The black-box phenomenon appeared most clearly in students' reliance on AI-generated outputs. R9 explained that students often trusted applications unquestioningly because digital systems rarely produced computational errors. R20 similarly described students entering data into AI tools without understanding the underlying mathematical procedures. These findings indicate a shift in epistemic authority from learners toward technological systems, requiring teachers to establish new forms of mediation and cognitive accountability.

Several teachers developed intuitive didactic responses to maintain students' epistemic responsibility. R21 required students to complete manual calculations before using GeoGebra, while R9 implemented a "Prove the Output" rule requiring students to justify digital results manually. Such strategies reflect emerging forms of technological didactic contracts intended to balance technological efficiency with conceptual reasoning.

Participants from rural schools also reported infrastructural constraints, including unstable internet connections and limited student device ownership. These findings confirm that technology integration challenges are not solely pedagogical but also ecological and structural.

3.1.3 Theme 3: Complexity of Classroom Management and Didactic Differentiation

The third theme emerged with 29 references. R9 narrated this experience sharply:

" In PjBL, each group may have a different modeling approach and type of calculation error." (R9)

The free-rider phenomenon also emerged consistently. R21 described situations in which only one or two students actively worked while others remained passive. Teachers responded by developing individual role structures, layered responsibilities, and facilitative questioning strategies to increase accountability. These findings align with research showing that formative assessment and individual accountability structures reduce free-rider effects in collaborative learning [27].

3.1.4 Theme 4: Specific Didactic Challenges for Statistics Material

The fourth theme generated the highest density of references. Teachers identified interpreting data and drawing conclusions as the most difficult aspects of statistics projects. R21 explained that students could create tables and graphs correctly but struggled to interpret the data in real-world contexts.

Misconceptions regarding measures of central tendency and variability repeatedly appeared. Students frequently assumed that datasets with identical means were equivalent despite differing distributions. Confusion between correlation and causality also emerged strongly. R9 illustrated this through students concluding that taller students achieved better.

3.1.5 Theme 5: Assessment Dilemma between Group Products and Individual Understanding

The fifth theme emerged in 23 references. Teachers experienced difficulty distinguishing individual conceptual understanding from collective project products. R9 described the challenge of identifying which students genuinely understood the mathematics underlying group outputs.

Teachers responded by developing layered assessment systems combining product evaluation, process monitoring, reflective journals, and oral questioning. R21 implemented a three-tier system consisting of product assessment, individual process journals, and post-project oral quizzes. These practices indicate that assessment in technology-integrated PjBL requires diagnostic and formative dimensions rather than relying solely on final products.

3.1.6 Theme 6: Teachers' Reflective Didactic Work

The final theme, with 28 references, emerged as a reflective response to previous challenges. Teachers described scaffolding strategies, reflective journals, phased checkpoints, and post-project debriefing sessions as essential components of successful PjBL implementation. R9 explained:

> *" I always set aside a special meeting after a project is completed for debriefing." (R9)*

This reflective process repositioned mathematical concepts at the center of learning after students completed project activities. Teachers interpreted reflection not as an optional stage but as a necessary didactic mechanism ensuring conceptual consolidation.

3.2. Discussion

The findings demonstrate that the didactic challenges experienced by mathematics teachers form an interconnected structure rather than isolated technical obstacles. Teachers continuously negotiated tensions between activity and knowledge, tool and concept, collaboration and individual accountability, and process and product. This confirms that meaningful mathematics learning requires careful orchestration of didactic situations.

Theme 1 strengthens the argument that successful PjBL depends not on the existence of projects themselves but on the quality of designs that maintain alignment with mathematical understanding. Teachers consistently interpreted projects as vehicles for conceptual understanding rather than ends in themselves.

Theme 2 offers one of the most significant conceptual contributions of this study through the distinction between technology-as-media and technology-as-cognitive-tool. The findings reveal that teachers predominantly integrated technology during the presentation and data-processing phases, while underutilizing it during guiding-question formulation, conceptual exploration, and collaborative reasoning. This pattern reflects the technology-as-media paradigm in which technology merely delivers or displays information.

The technology-as-cognitive-tool paradigm, as proposed by TPACK, positions technology as part of students' mathematical reasoning processes. Within this perspective, GeoGebra becomes a tool for generating investigative questions, Google Classroom functions as a collaborative reasoning environment, and Quizizz serves as a diagnostic feedback mechanism throughout project implementation rather than only in evaluation phases.

Smaldino, Lowther, and Mims emphasize that effective instructional technology integration requires pedagogical alignment among learning objectives, learner characteristics, and selected technologies. Mayer similarly argues that multimedia supports meaningful learning only when learners actively organize and integrate information. The findings, therefore, indicate that technology integration quality depends less on the sophistication of tools and more on how technologies mediate conceptual reasoning processes.

The findings regarding AI dependency deepen discussions about technological mediation in mathematics education. Teachers experienced shifts in epistemic authority from students toward applications and AI systems, particularly when students accepted automated outputs without conceptual verification. These experiences strengthen the argument that AI integration transforms relationships within the didactic system and requires new epistemic contracts that regulate students' cognitive responsibilities. Recent developments in AI-supported education increasingly highlight the importance of balancing automation efficiency with human conceptual reasoning, particularly in mathematics learning contexts where procedural outputs can obscure conceptual understanding.

Theme 3 clarifies that classroom management in PjBL represents a didactic engineering challenge rather than merely a managerial issue. Theme 4 demonstrates that statistics learning generates multilayered conceptual difficulties involving interpretation, reasoning, and causal inference [28]. Theme 5 confirms that assessment in PjBL requires multidimensional strategies capable of capturing both collaborative products and individual understanding. Theme 6 positions reflective didactic work as a core professional competency, enabling teachers to reconnect projects, technology, and mathematical concepts.

The findings also reveal the importance of institutional and infrastructural contexts within Indonesian schools. Teachers from rural areas reported unstable internet access, unequal device ownership, and limited opportunities for technology-focused professional development [29]. These contextual realities indicate that the successful implementation of technology-integrated PjBL requires systemic institutional support alongside teachers' pedagogical competencies [30].

Theoretically, this study proposes expanding the classical didactic tetrahedron into a pentagonal didactic structure comprising teacher, student, mathematics, technological artifact, and project (authentic problem) [31]. This proposed structure illustrates how projects and technological artifacts simultaneously mediate epistemic interactions within contemporary mathematics learning environments. Practically, the findings recommend: (1)

integrating TPACK-based technology across all PjBL phases; (2) developing technological didactic contracts regulating students' cognitive responsibilities; (3) implementing layered assessments measuring products, processes, and individual understanding; and (4) strengthening teacher professional development in statistics pedagogy, AI literacy, and digital didactic competencies.

4. CONCLUSION

This study reveals that technology-integrated Project-Based Learning (PjBL) in mathematics poses complex didactical challenges in balancing mathematical concepts, project activities, technology use, classroom interaction, and assessment practices. The findings identify six interconnected challenges involving conceptual tension, technology functioning as a didactic black box, classroom management complexity, statistical reasoning difficulties, assessment dilemmas, and reflective didactical work. One of the main contributions of this study is the distinction between technology-as-media and technology-as-cognitive-tool, showing that technology is still predominantly used for presentation and procedural purposes rather than as a mediator of mathematical reasoning. Theoretically, this study proposes expanding the classical didactic tetrahedron into a pentagonal didactic structure comprising teacher, student, mathematics, technological artifact, and project, emphasizing the multidimensional relationships in contemporary mathematics learning. In practice, the findings highlight the importance of TPACK-based technology integration across all PjBL phases, technological didactic contracts, layered assessment systems, and professional development related to statistics pedagogy, AI literacy, and digital didactic competence. This study is limited to phenomenological interpretations based on written responses from 22 mathematics teachers in North Sumatra; therefore, future studies are recommended to include classroom observations, longitudinal designs, and broader educational contexts. The findings contribute to mathematics education research, teacher professional development, and educational policy discussions regarding meaningful technology integration in mathematics learning.

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