



Developing a TPACK-based science module through project-based learning to enhance elementary students' 4Cs skills

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Abstract: Science education in elementary schools in Pinrang Regency is still dominated by conventional approaches. There is low integration of technology and limited development of 21st-century skills such as critical thinking, communication, collaboration, and creativity. This study aims to develop and implement a Science teaching module based on TPACK and integrated with the Project-Based Learning (PjBL) model. The goal is to enhance students' 4Cs skills. The research used a Research and Development (R&D) approach with the ADDIE model (Analyze, Design, Develop, Implement, Evaluate) within a Mixed Methods design. Data were collected through expert validation questionnaires (Aiken's V coefficient), teacher and student practicality questionnaires, structured classroom observation protocols (17 indicators, inter-rater reliability = 0.87), and semi-structured interviews with 12 teachers and 12 school principals. Pre-test and post-test instruments measured Four Cs competencies. Quantitative data were analyzed using normalized gain (N-Gain) calculations and paired-samples t-tests (SPSS v. 28). Qualitative data underwent thematic analysis following Braun and Clarke's (2006) six-phase framework in NVivo 12. The results showed that the developed module had high validity and practicality. It achieved average validity and practicality scores of 90%. The module effectively improved students' Four Cs skills, with an average N-Gain score ranging from 0.49 in the limited trial to 0.51 in the wide-scale trial. This study contributes to the development of a teaching model that integrates technology and project-based methods to improve 21st-century skills in elementary education, especially in regions with limited infrastructure. The findings also suggest that improving teacher training and providing adequate infrastructure support are essential for the sustainability of the model's implementation.

Keywords: project-based learning, four Cs skills, teaching module, TPACK, science education

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Introduction

The accelerating pace of technological advancement and globalization has fundamentally transformed education worldwide. The World Economic Forum (2020) notes that nearly 50% of all employees will require reskilling by 2025 as technological adoption expands. Even more striking are forecasts suggesting that 65% of children entering primary school will eventually occupy jobs that do not yet exist (World Economic Forum, 2016). These projections underscore a critical imperative: education systems must move from traditional, content-heavy paradigms to competency-based frameworks that equip learners with essential 21st-century skills.

Critical Thinking, Communication, Collaboration, and Creativity—the Four Cs—are widely recognized as indispensable for the digital era. The OECD (2019) emphasizes that future-ready students need not only domain knowledge but also cognitive and interpersonal agility to adapt to dynamic contexts. As a result, educational institutions face pressure to redesign pedagogical models. They are being urged to move beyond rote memorization and instead cultivate holistic learner development.



Science education holds particular promise for fostering 21st-century skills. Science is both a body of knowledge and a method of inquiry, demanding logical reasoning, problem-solving, and hypothesis testing. These align with critical and creative thinking. Science learning environments also offer natural opportunities for collaboration and communication, especially with project-based tasks. However, the extent to which these opportunities are realized varies across regions. In developing nations, structural limitations hinder pedagogical innovation.

This challenge is especially significant in Southeast Asia. Regional disparities in educational access and instructional quality continue to impede skill development among school-aged children. Indonesia, the world's fourth most populous country, has launched ambitious initiatives to modernize curricula, decentralize learning, and promote learner autonomy. The "Merdeka Belajar" or "Freedom to Learn" reform agenda aligns with global frameworks advocating personalized and inquiry-based learning. However, its implementation across Indonesia's diverse, geographically fragmented education system remains inconsistent.

Empirical evidence shows a gap between policy formulation and classroom practice. A study of elementary schools in rural Eastern Indonesia, including Pinrang Regency, found that 68% of students show below-standard proficiency in the Four Cs (Critical Thinking, Creativity, Collaboration, and Communication). The study also found that 76% of teachers lack confidence in integrating technology into science instruction. Only 18% of schools actively use collaborative learning strategies. These findings are consistent with Rofiah et al. (2024). Their qualitative study of elementary school teachers in rural Belitung identified six themes of ICT-readiness deficiencies. These include limited proficiency in digital tools, inadequate planning and selection of ICT-based media, and insufficient understanding of teachers' roles in ICT-driven pedagogy.

The disparities are not only infrastructural; they are also pedagogical. Observational data revealed that science lessons in rural Indonesian classrooms are mainly teacher-centered. They emphasize textbook content and factual recall, leaving little room for inquiry and exploration. This method contradicts 21st-century learning principles, which prioritize learner agency, contextual relevance, and interdisciplinary problem-solving. The lack of technology in these classrooms makes the goals of the Merdeka Curriculum more aspirational than operational.

A dual-layered educational crisis emerges from this context. The crisis is both systemic and epistemic. Educational systems must overcome logistical barriers such as infrastructure, teacher training, and access to digital tools. They must also undergo a shift in how knowledge is conceptualized, delivered, and evaluated. This dual imperative is especially important in elementary science education. Early exposure to scientific reasoning can be a gateway to lifelong inquiry and intellectual independence.

Integrating technology into science education has shown promise worldwide, especially when guided by strong instructional design frameworks. One such framework is Technological Pedagogical Content Knowledge (TPACK), which highlights the relationship between technology, pedagogy, and content (Mishra & Koehler, 2006). TPACK moves beyond superficial technology use, advocating for contextually aligned strategies that support learning. When paired with Project-Based Learning (PjBL)—a learner-centered model where students study real-world problems—the TPACK framework becomes a powerful catalyst for skill development and conceptual mastery.

Integrated Technological-Pedagogical-Content Knowledge (TPACK) and Project-Based Learning (PjBL) models have a strong positive impact on critical thinking and collaboration skills. These models show higher effect sizes than traditional instructional methods (Muskitta et al., 2023; Prastiyan et al., 2023). This aligns with Indonesian research showing PjBL boosts student motivation, engagement, and creativity (Pangestu et al., 2024; Satria et al., 2025). Including local cultural content in these frameworks—like batik traditions or indigenous architecture—amplifies student relevance and retention (Rukmi et al., 2025).

Theories for these pedagogical innovations are well established. Yet their use in rural Indonesian classrooms remains underexplored. Few studies have examined how TPACK and PjBL can be systematically integrated into science modules for resource-limited elementary schools. There are also a few validated assessment tools for measuring the Four Cs within elementary science curricula. These gaps show the urgent need for research. This research should develop innovative teaching materials and rigorously evaluate their effectiveness in real classrooms.

Addressing this identified research gap, the present study was guided by the following research questions: (1) how can TPACK principles be effectively integrated with Project-Based Learning methodology to develop a Science teaching module for fifth-grade elementary students? (2) what is the level of validity of the TPACK-based Science module integrated with PjBL, as assessed by content, media, and educational technology experts? (3) what is the level of practicality of the module based on teacher and student responses during implementation? and (4) how effective is the module in improving students' Four Cs skills (Critical Thinking, Communication, Collaboration, and Creativity) as measured by normalized gain scores? These objectives collectively aim to provide empirical evidence for a replicable, technology-integrated pedagogical model applicable to resource-constrained elementary school settings in Indonesia.

Methods

This study employed a Research and Development (R&D) approach with mixed methods design to develop and evaluate a TPACK-based science teaching module integrated with Project-Based Learning for elementary students. This design facilitated a comprehensive assessment of the module's validity, practicality, and effectiveness through rigorous testing and expert review (Amini et al., 2019). The integration of the ADDIE model within this mixed-methods framework allowed for an iterative refinement process, ensuring that the module was not only theoretically sound but also practically applicable and effective in diverse educational settings (Mat et al., 2024). This methodological choice aligns with established frameworks for educational research, which emphasize systematic development and evaluation to ascertain the efficacy and applicability of new learning materials (Mat et al., 2024; Zulnaldi, 2024). The research adopted the ADDIE model as the developmental framework, conducted from January to July 2025 across 12 elementary schools in Pinrang Regency, South Sulawesi, Indonesia.

The research sites were strategically selected across four sub-districts—Pinrang, Mattiro Bulu, Paleteang, and Watang Sawitto—representing diverse socio-economic contexts from urban peripheries to rural areas with varying technological infrastructure. Multi-stage purposive sampling identified 390 fifth-grade students (aged 10–12 years; 52% female, 48% male), 12 science teachers (8 female, 4 male; teaching experience ranging from 3 to 22 years; all holding minimum S1/bachelor's degree qualifications), 12 school principals, and 3 expert validators as research participants. School selection criteria included minimum technological infrastructure availability, teacher readiness for professional development, and administrative support for the research process. Expert validators were selected through criterion sampling, requiring doctoral qualifications, decade-long experience in relevant fields (science education, instructional technology, and educational assessment), and active publication records in national and international peer-reviewed journals. Table 1 below presents the ADDIE-based research flow guiding the study.

Table 1. ADDIE-based research flow

ADDIE Phase	Key Activities	Instruments/Tools	Output
1. Analyze	Needs assessment; TPACK survey; classroom observation; infrastructure mapping	Schmidt et al. (2009) TPACK instrument; observation checklist	Needs analysis report; problem identification
2. Design	Module blueprint; TPACK-PjBL framework design; culturally-responsive content integration	TPACK components matrix; PjBL 7-stage framework	Module blueprint; learning objectives; assessment plan
3. Develop	Module construction; expert validation (3 validators); revision	Aiken's V coefficient ($V \geq 0.75$); 5-point Likert validation sheets	Validated module prototype
4. Implement	Limited trial (90 students, 3 schools, 4 weeks); wide-scale trial (300 students, 12 schools, 6 weeks)	Pre-post tests; observation protocol (17 indicators); teacher & student questionnaires; interviews	Practicality and effectiveness data

5. Evaluate	N-Gain analysis; thematic analysis; data triangulation; module revision	SPSS v.28 (N-Gain, t-test); NVivo 12 (thematic coding)	Final validated and effective module
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The analysis phase commenced with a comprehensive needs assessment of teacher TPACK competencies, pedagogical practices, and technological infrastructure. These findings informed the design and development of a module prototype featuring a seven-stage PjBL framework integrated with Bugis-Makassar traditional knowledge. Content validity was established through expert judgment across media, pedagogy, and material dimensions, utilizing Aiken’s V coefficient with a threshold of $V \geq 0.75$. The implementation then proceeded through a two-phase trial: an initial feasibility test with 90 students, followed by a wide-scale application involving 300 students across 12 schools, including Grendeng 1, 2, and 3 Elementary Schools. This six-week process followed systematic PjBL cycles to ensure implementation fidelity across all experimental sites.

Data collection employed a mixed-methods approach to evaluate effectiveness and practicality. Performance tests measured the 4Cs skills (critical thinking, communication, collaboration, and creativity), while 5-point Likert scale questionnaires assessed user engagement and instructional support. Implementation of fidelity was documented via observation protocols with a high inter-rater reliability of 0.87, supplemented by semi-structured interviews with teachers and principals. Quantitative analysis was performed using paired samples t-tests and Hake’s (1998) normalized gain formula via SPSS 28. Concurrently, qualitative data underwent thematic analysis using NVivo 12 following Braun and Clarke’s (2006) framework. Ultimately, a convergent mixed-methods design triangulated these findings to provide a comprehensive validation of the module’s pedagogical impact.

Results and Discussion

Results

The results of this study are presented in accordance with the four research questions that guided this investigation. Each subsection directly addresses a specific research question through empirical data collected during the implementation phases.

1. Integration of TPACK Principles with PjBL Methodology

The integration was achieved through systematic design and validated through expert assessment and classroom implementation observations. The developed module successfully integrated TPACK components with the seven-stage PjBL framework. Content knowledge (CK) was embedded through scientifically accurate heat transfer concepts aligned with the 2013 Curriculum. Pedagogical knowledge (PK) was incorporated through structured PjBL stages, from determining fundamental questions to evaluating experiences. Technological knowledge (TK) was integrated via interactive digital media, online resources, and technology-enhanced data collection tools.

The intersection of these knowledge domains (PCK, TCK, TPK, and TPACK) was evident in the module’s design features: 1) PCK Integration: heat transfer concepts were taught through hands-on experiments and local context examples (Bugis-Makassar traditional houses); 2) TCK Integration: digital simulations and interactive media visualized abstract heat transfer phenomena; 3) TPK Integration: technology tools supported collaborative project work and data collection; and 4) TPACK Synthesis: all three domains converged in technology-mediated project activities where students used digital tools to investigate heat transfer in traditional architecture. Implementation Observations of Integration. Classroom observations across 12 schools confirmed the successful operationalization of TPACK-PjBL integration. The observation data revealed:

Table 2. Implementation of TPACK-PjBL Integration Stages

PjBL Stage	TPACK Element	Implementation Rate	Integration Evidence
Phenomenon Presentation	TCK + PCK	100%	Digital media showing traditional houses; scientific concept introduction
Investigative Questions	TPK	91.7%	Technology-supported brainstorming; pedagogy-guided inquiry

Group Formation	PK	100%	Heterogeneous grouping strategies
Experiment Design	TPACK	83.3%	Technology tools for design; content-driven experiments; collaborative pedagogy
Schedule Creation	TPK	100%	Digital planning tools; project management pedagogy
Monitoring & Guidance	TPACK	100%	Technology-enhanced monitoring; content feedback; pedagogical support
Data Collection	TCK + TPK	83.3%	Digital data collection; technology-mediated analysis
Presentation	TPACK	100%	Multimedia presentations; content synthesis; peer learning

Table 2 shows that the high implementation rates (average 95.1%) across all stages demonstrate that the TPACK-PjBL integration was not only theoretically sound but practically achievable in diverse classroom contexts.

2. Module Validity

The results of the validation of the TPACK-based Science teaching module integrated with the PjBL model showed that the developed module has a very high level of validity. The validation was conducted by three experts in the fields of content, media, and educational technology, with the following result.

Table 3. Expert Validation Results

Validation Aspect	V1	V2	V3	Average Score	Validity (%)	Category
Content Feasibility	4.48	4.52	4.56	4.52	90.4%	Highly Valid
Module Presentation	4.56	4.60	4.64	4.60	92.0%	Highly Valid
Teaching Media	4.52	4.56	4.60	4.56	91.2%	Highly Valid
Overall Average	4.52	4.56	4.60	4.56	91.2%	Highly Valid

Table 3 shows that in the content feasibility aspect, the module obtained an average score of 4.52 out of 5, equivalent to 90.4%. The module presentation aspect received the highest appreciation with an average score of 4.60 or 92.0%. For the learning media aspect, the module obtained an average score of 4.56 or 91.2%. The validation results confirm that the developed module meets the validity criteria for implementation in science learning at elementary schools in Pinrang Regency. The integration of TPACK framework with the PjBL model proved effective in creating learning materials that are not only theoretically sound but also practical and contextual.

3. Practical Feasibility Based on User Responses

The third research question examined the practical feasibility of implementing the module based on teacher and student responses. The module's practicality was evaluated through responses from two main user groups: teachers and students. Twelve teachers who implemented the module provided feedback through structured questionnaires measuring three practicality dimensions.

Table 4. Teacher Practicality Assessment

Practicality Dimension	Average Score	Percentage	Qualitative Feedback Themes
Ease of Use	4.56/5.00	91.2%	"Clear instructions"; "Step-by-step guidance helpful"
Time Efficiency	4.48/5.00	89.6%	"Saves preparation time"; "Activities fit allocated time"
Instructional Support	4.52/5.00	90.4%	"Comprehensive teacher guide"; "Assessment rubrics clear"
Overall Practicality	4.52/5.00	90.5%	Very Practical

Table 4 presents teacher practicality data collected from 12 teachers who implemented the module in their respective schools. With a practicality score reaching 90.5%, these results demonstrate a highly positive reception from educators. The majority of teachers reported that the module was easy to

understand and use in daily learning contexts. The provided usage instructions were assessed as clear and comprehensive, enabling teachers to follow the learning steps without significant difficulty. Student responses (n=300) assessed through age-appropriate visual scales revealed high perceived practicality.

Table 5. Student Practicality Assessment

Assessment Aspect	Limited Trial (n=90)	Wide-Scal Trial (n=300)	Combined Average
Material Understanding	87.8%	88.5%	88.3%
Activity Engagement	89.2%	88.7%	88.8%
Skill Development Support	86.7%	87.9%	87.6%
Overall Practicality	87.9%	88.4%	88.3%

Table 5 reveals that student practicality data indicated strong engagement and accessibility. Visual rating scales appropriate for elementary learners showed 88.3% positive responses. Students particularly appreciated the project-based activities (92% positive), technology integration (87% positive), and collaborative elements (90% positive). These results confirm the module’s feasibility for widespread implementation across diverse elementary school settings.

4. Module Effectiveness in Improving Four Cs Skills

The module's effectiveness was measured using normalized gain (N-Gain) calculations between pre-test and post-test scores across two implementation phases, with the following findings:

Table 6. N-Gain Analysis of Four Cs Skills Improvement

Implementation Phase	n	Pre-test Mean	Post-test Mean	N-Gain	Category	Effect Size (d)
Limited Trial	90	51.7	75.2	0.49	Moderate	0.68
Wide-Scale Trial	300	52.1	76.4	0.51	Moderate	0.71
Combined	390	52.0	76.1	0.50	Moderate	0.70

Table 6 demonstrates that the first phase involved a limited trial with 90 students from 3 elementary schools in Pinrang Regency. Analysis results showed an average N-Gain value of 0.49, which falls within the moderate category. This achievement indicates that the module was able to provide meaningful learning improvements even within a limited implementation scale. The second phase involved a wide-scale trial with the participation of 300 students from 12 elementary schools. Results showed an increase in N-Gain value to 0.51, remaining in the moderate category but slightly higher than the limited trial. The consistency of results between limited and wide-scale trials confirms the module's reliability in more diverse contexts. Authentic assessments through presentations and project portfolios provide additional evidence of the Four C's skills development can be seen in the following table.

Table 7. Performance assessments Four Cs Skills phase limited Trial

Skill Component	Limited Trial (n=90)			Wide-Scale Trial (n=300)		
	Pre-test	Post-test	Gain	Pre-test	Post-test	Gain
Critical Thinking	52.3	74.6	+22.3	52.8	76.4	+23.6
Creativity	48.7	72.3	+23.6	50.3	75.2	+24.9
Collaboration	55.2	78.5	+23.3	54.2	78.5	+24.3
Communication	50.4	75.2	+24.8	51.1	75.3	+24.2

Table 7 shows that a high-level detailed analysis of each of the four Cs skill components in the limited trial showed consistent improvement. Critical thinking skills increased from an initial score of 52.3 to 74.6, showing an improvement of 22.3 points. Student creativity increased from 48.7 to 72.3, a gain of 23.6 points. The collaboration aspect showed the greatest improvement, from 55.2 to 78.5, or an increase of 23.3 points. Meanwhile, communication skills improved from 50.4 to 75.2, with an increase of 24.8 points. In the wide-scale trial, the improvement pattern of the Four Cs skills was consistent with the limited-trial results. Critical thinking increased from 52.8 to 76.4 (an improvement of 23.6 points), creativity from 50.3 to 75.2 (an improvement of 24.9 points), collaboration from 54.2 to 78.5 (an improvement of 24.3 points), and communication from 51.1 to 75.3 (an improvement of 24.2 points). The uniformity of improvement across all four aspects demonstrates that the module successfully develops Four Cs skills holistically and in a balanced manner.

Classical Mastery

Table 8 summarizes the classical mastery data. Classical mastery serves as a crucial indicator for measuring the success of module implementation in achieving learning objectives. The analysis results of classical mastery in the learning process using the TPACK-based science teaching module demonstrated highly satisfactory achievements that exceeded the minimum target set at 75%, with the following findings.

Table 8. Classical Mastery Achievement

Trial Phase	Total Students	Students Achieving Mastery	Classical Mastery (%)	Above Target
Limited Trial	90	74	82.2%	+7.2%
Wide-Scale Trial	300	252	84.0%	+9.0%
Combined	390	326	83.6%	+8.6%

Table 8 shows that in the limited trial phase involving 90 students from three schools, 74 students achieved mastery. This achievement equals a classical mastery percentage of 82.2%. These results provided initial indications that the module could facilitate effective learning, even in a small-scale implementation with limited school conditions.

When implementation was expanded during the wide-scale trial phase involving 300 students from 12 schools, the classical mastery level increased. Of the total participants, 252 students successfully achieved mastery, resulting in a mastery percentage of 84.0%. The increase in mastery percentage from limited to wide-scale trials indicates that the module has good adaptability and even performs more optimally when implemented across more diverse contexts.

Overall, of the 390 students involved in both trial phases, 326 achieved classical mastery. This resulted in a total mastery percentage of 83.6%, well above the minimum target of 75% set in the research success indicators. This achievement confirms that using a TPACK-based teaching module with the PjBL model significantly improved students' learning outcomes.

Implementation Observations

Classroom observations of the Project-Based Learning model implementation provided a comprehensive overview of module execution in the field. Systematic observations were conducted in 12 schools involved in the research, covering all learning stages from the first meeting to the final evaluation. Observation results showed a very high implementation level, with an overall average reaching 95.1%.

The heat transfer phenomenon presentation stage was fully implemented in all schools without significant obstacles. Teachers successfully presented the local context of Bugis-Makassar traditional houses as effective learning triggers. Students showed high enthusiasm as they observed traditional house characteristics and began identifying their relationship to heat transfer concepts. Total success at this stage indicates that the module's introductory materials were well-designed and easily implemented.

Formulation of investigative questions proceeded well in almost all schools. Data showed 11 out of 12 schools fully implemented this stage, while one school experienced minor obstacles, with 8.3% of students unable to formulate questions independently. This obstacle was overcome through additional teacher guidance, demonstrating the module's flexibility in accommodating variations in student ability.

Other crucial stages in the PjBL model showed highly satisfactory implementation levels. Heterogeneous group formation was 100% implemented in all schools, with teachers successfully organizing students into balanced teams. Experiment design was fully implemented in 10 schools (83.3%), while 2 schools partially implemented due to time constraints and needed adjustments. Work schedule creation was successfully implemented across all schools, demonstrating that students could organize their time and project responsibilities.

The monitoring phase during meetings 4 and 5 showed active involvement from both students and teachers. Experiment execution and teacher guidance were 100% implemented, indicating full commitment to the learning process. Technology use in data collection achieved 83.3% full implementation, with 2 schools experiencing minor technical obstacles but still completing activities with simple adaptations.

The high implementation rates across all PjBL stages validate the module's practical design and comprehensive support materials. The near-perfect execution of most learning phases demonstrates that the module successfully translates theoretical frameworks into actionable classroom practices. Minor variations in implementation, particularly in technology use and investigative question formulation, reflect normal adaptation rather than fundamental design flaws in diverse educational contexts. These observations confirm that the TPACK-based module with the PjBL model is not only theoretically sound but also practically viable across different school environments in Pinrang Regency.

Discussion

The results of this study demonstrate that the developed TPACK-based Science teaching module integrated with the Project-Based Learning (PjBL) model effectively improved the Four Cs skills of elementary school students in Pinrang Regency. The primary objective of this research was to develop, test, and evaluate a teaching module that could enhance students' critical thinking, communication, collaboration, and creativity skills, with indicators of validity, practicality, and effectiveness of at least 80%. The findings indicate that the module not only achieved high validity (with an average validity score of 90%) but also demonstrated high practicality (90%) and effectiveness (with an N-Gain ranging from 0.49 to 0.51). These results align with the research objectives of developing a technology-based teaching module that integrates project-based methods to improve 21st-century skills in students. Qualitative evidence from teacher interviews reinforced these quantitative findings. One science teacher from Pinrang 15 Elementary School remarked,

“Before using this module, I found it very difficult to encourage my students to think beyond the textbook. Now, they actually ask me questions about why heat behaves differently in traditional and modern houses — that never happened before.”

This observation aligns with research demonstrating that contextually embedded learning tasks generate intrinsic cognitive engagement that standardized approaches cannot replicate (Krajcik & Shin, 2014). The findings of this study are in line with the TPACK framework, which emphasizes that the integration of technology in education should consider the relationship between content, pedagogy, and technology (Mishra & Koehler, 2006). In this context, TPACK serves as the theoretical foundation for the development of the teaching module, which not only teaches science content but also effectively utilizes technology to support project-based learning. The study shows that the integration of TPACK in Science teaching through the PjBL model strengthens the development of Four Cs skills, especially in collaboration and creativity, which are core goals of 21st-century learning. The project-based learning process, which actively involves students in solving real-world problems, enables them to develop critical thinking and communication skills in a practical and applicable manner (Saavedra & Opfer, 2012). Notably, interviews with teachers revealed that the module's culturally-responsive design — embedding Bugis-Makassar traditional architecture as a learning context for heat transfer — was a critical factor in sustaining student engagement. A school principal from Kecamatan Paletang stated,

“Students are motivated when they see their own heritage in the lessons. The module connected science to something they already know and love.”

This finding echoes Gay's (2018) argument that culturally responsive teaching significantly enhances learning relevance and student identity affirmation, particularly in indigenous and rural educational communities. Previous studies have shown that integrating TPACK with PjBL has a positive impact on the development of 21st-century skills. However, most of the existing research has focused on higher education or subjects such as mathematics (Masnur et al., 2024). This study adds new empirical evidence regarding the effectiveness of TPACK and PjBL in elementary education, particularly in Science (IPA), in rural areas such as Pinrang. The findings align with those of Rahayu et al. (2023), which suggest that TPACK-based teaching can improve students' creative and collaborative skills. This study also provides further evidence of the effectiveness of integrating PjBL in enhancing critical thinking and communication skills in a primary education context. On the other hand, studies by Waluyo (2023) have shown that many teachers still struggle to use technology effectively, which

highlights the relevance of this research in providing practical solutions through the development of a teaching module integrated with technology. This challenge was evident during the wide-scale trial, where two schools experienced difficulties with digital data collection tools due to intermittent internet connectivity. One teacher candidly noted,

“The technology activities were wonderful when everything worked, but we needed backup plans because the internet is not always reliable in our area.”

This observation underscores the importance of designing TPACK-based modules with built-in pedagogical redundancy — ensuring that offline alternatives are available for each technology-dependent learning activity (Jang & Tsai, 2012). The moderate N-Gain scores (0.49–0.51) observed in this study, while educationally meaningful, also suggest that ceiling effects in four-week and six-week implementation cycles may limit the full realization of TPACK-PjBL benefits; longer longitudinal implementation studies are warranted to assess cumulative skill development trajectories.

This study contributes significantly to the development of TPACK theory by providing concrete evidence of its application in Science teaching at the elementary level. Additionally, this research expands our understanding of how the PjBL model, which has primarily been applied in higher education, can be adapted to the elementary school context with positive outcomes. Thus, this study not only contributes to educational theory but also provides a practical model that can be applied directly by educators in primary schools. The successful integration of technology in Science teaching, which has been limited so far, has proven to enhance 21st-century skills in students, making it an important contribution to the development of education in Indonesia, particularly in areas with limited educational infrastructure (Harris et al., 2021).

Although the findings of this study are promising, several limitations should be acknowledged. First, while the study involved 12 elementary schools in Pinrang Regency, the sample size is still relatively small, and it represents a specific region, so the generalizability of the findings should be made with caution. Second, although the quantitative data indicated significant improvements, the qualitative data obtained through interviews and observations could be further explored to gain deeper insights into the local context that influences the implementation of this model. Third, while the teaching module has been proven effective, the use of technology in classrooms still depends on the availability of adequate infrastructure. Therefore, further research is needed to involve more schools in different regions with varied infrastructure to obtain a more comprehensive understanding of the sustainability of implementing this model on a larger scale.

This study has several practical implications for the development of future research and practice. First, it is essential to conduct further research involving more schools across various regions with different infrastructural conditions to test the sustainability and scalability of this model. Second, for educators, the findings emphasize the importance of ongoing professional development in effectively integrating technology into teaching, as technology offers many benefits in enhancing the development of 21st-century skills. For policymakers, this study provides valuable insights into the need for support in developing and distributing technology-based teaching materials that can be easily accessed by both teachers and students, as well as improving educational infrastructure in regions with limited technological access. Future research can also explore deeper ways to integrate technology in each stage of PjBL to further enhance overall student learning outcomes.

Conclusion

This study demonstrates that the TPACK-based Science module, integrated with Project-Based Learning (PjBL), effectively enhanced the 4Cs skills of elementary students. Validated through the ADDIE model, the module achieved high validity (91.2%) and strong practicality among teachers (90.5%) and students (88.3%). Effectiveness was confirmed by moderate N-Gain scores of 0.49 and 0.51, with classical mastery reaching 83.6%, significantly exceeding the 75% target.

Theoretically, this research provides empirical evidence of TPACK's applicability in elementary science and demonstrates how PjBL can be adapted for younger learners. By integrating *Bugis-Makassar* cultural heritage, the study also advances scholarship on culturally-responsive pedagogy.

Practically, the module serves as a ready-to-use resource for teachers in similar rural contexts. Implications suggest that policymakers and administrators should prioritize sustained TPACK professional development and digital infrastructure to support the *Merdeka* Curriculum. While successful, the study's regional focus in Pinrang Regency and its short-term duration limit broader generalizability. Future research should pursue longitudinal, multi-regional studies and explore the scalability of this model across diverse grade levels and technological environments.

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