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Integrating Project-Based Learning and TPACK to Improve Students' Collaboration and Communication Skills in Elementary Mathematics

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ABSTRACT

This study aims to examine the integration of Project-Based Learning (PjBL) and Technological Pedagogical and Content Knowledge (TPACK) to improve students' collaboration and communication skills in elementary Mathematics learning. This study employed a Classroom Action Research (CAR) design based on the Kemmis and McTaggart model, consisting of planning, action, observation, and reflection. The research was conducted in three cycles involving 25 fourth-grade students of Class IV C at SDS Islam Al-Falah 2 Jambi, Indonesia. Data were collected through collaboration and communication observation sheets, teacher activity observations, interviews, and documentation. The data were analyzed using descriptive quantitative and qualitative analysis. The success criterion was set at a minimum average achievement of 76% for both collaboration and communication skills. The results showed a consistent improvement in students' collaboration and communication skills following the implementation of PjBL integrated with TPACK. Collaboration increased from 42.8% in the pre-cycle, categorized as very poor, to 62.8% in Cycle I, 76.6% in Cycle II, and 90.0% in Cycle III, categorized as very good. Similarly, communication increased from 40.6% in the pre-cycle to 61.6% in Cycle I, 76.4% in Cycle II, and 90.2% in Cycle III. Both indicators exceeded the 76% success criterion in Cycle II and demonstrated further improvement in Cycle III. This study contributes empirical evidence that integrating PjBL with TPACK can provide structured and meaningful opportunities for students to collaborate, share responsibilities, discuss mathematical ideas, communicate reasoning, and present project outcomes. The findings indicate that the improvement was supported by the synergy between PjBL as a student-centered learning model and TPACK as a framework for aligning technology, pedagogy, and Mathematics content.

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1. INTRODUCTION

Elementary education plays an important role in developing students' cognitive, social, and character-related capacities as a foundation for addressing the learning and life demands of the future [1]. Learning is no longer directed solely toward the acquisition of knowledge but also toward the development of skills that enable students to participate actively in the learning process [2]. In line with the implementation of the Merdeka Curriculum, learning is increasingly oriented toward student-centered and contextual approaches that provide opportunities for students to construct knowledge through meaningful learning experiences. This condition requires a learning process that is not only oriented toward academic achievement but also capable of developing collaboration and communication skills as essential components of students' competencies.

Collaboration and communication skills play an important role in supporting students' success in the learning process [3]. Collaboration enables students to work together, share responsibilities, respect different opinions, and contribute to achieving common goals [4]. Meanwhile, communication enables students to convey ideas, explain their reasoning, express opinions, and respond to the ideas of others [5]. These two skills are closely interconnected because collaborative activities require students to communicate their ideas and understand the perspectives of group members. Mathematics learning provides a potentially valuable context for developing these skills because students are not only expected to obtain correct answers but also to explain their reasoning, discuss problem-solving strategies, and work together to solve mathematical problems [6].

However, classroom conditions indicate that students' collaboration and communication skills still need to be improved. An initial observation conducted on February 10, 2026, at SDS Islam Al-Falah 2 Jambi involving 25 students showed that students' collaboration skills were still in the low category. The highest score obtained was only 65%, while the class average was 42.8%, with no students reaching the moderate or high category. During group activities, only one or two students were actively involved in completing the tasks, whereas the remaining students tended to be passive, and some had not yet understood the tasks they were expected to perform. Similar conditions were observed in students' communication skills. The average communication score was only 40.6%, with the highest score reaching 65%. Some students lacked confidence in expressing their opinions, while others tended to remain silent or simply follow their peers' opinions. Student-to-student discussion was also limited, resulting in insufficient opportunities for students to express and explain mathematical ideas. These conditions were consistent with the students' mathematics learning outcomes at the pre-cycle stage, in which only 12 of the 25 students (48%) achieved the minimum mastery criterion (KKM) of ≥75, while 13 students (52%) did not meet the criterion, with a class average of 67.6.

These problems indicate the need for a learning model that provides students with broader opportunities to participate actively, collaborate, and communicate their ideas throughout the mathematics learning process. Project-Based Learning (PjBL) is a relevant model because it positions students as active participants in learning through project activities oriented toward solving particular problems or producing specific products [7]. The PjBL process enables students to work in groups, divide responsibilities, engage in

discussions, make decisions, and present their project outcomes [8]. These characteristics make PjBL potentially effective in creating a learning environment that supports the development of students' collaboration and communication skills.

Nevertheless, implementing PjBL in mathematics learning is not sufficient by simply assigning students project-based tasks. Project implementation needs to consider the alignment among learning objectives, the characteristics of mathematical content, pedagogical strategies, and the technologies employed [9]. The use of technology that is not integrated with learning objectives may result in technology functioning merely as an additional tool without making an optimal contribution to students' learning experiences. Therefore, the Technological Pedagogical Content Knowledge (TPACK) framework can be employed to ensure that technology is selected and utilized in alignment with the content being learned and the pedagogical strategies being implemented [10]. TPACK emphasizes the interrelationship among technological knowledge, pedagogical knowledge, and content knowledge, enabling technology to meaningfully support the learning process [11].

The integration of PjBL and TPACK has the potential to strengthen mathematics learning because the project characteristics provide opportunities for students to collaborate and communicate, while TPACK helps ensure that project activities, mathematical content, and technology are meaningfully interconnected. Through this integration, technology is not merely used as a medium for delivering instructional materials but becomes an integral part of students' activities in exploring information, completing tasks, developing products, and communicating project outcomes. Consequently, learning can provide students with more active, contextual, and meaningful learning experiences.

Several previous studies have demonstrated the potential of PjBL and TPACK in supporting the learning process. Saleha et al. [12], for example, found that the integration of PjBL and TPACK can support learning through the use of technology integrated with pedagogical approaches. Andriyani et al. [13] also reported that PjBL can improve students' collaboration skills in elementary mathematics learning. Meanwhile, Zhauna et al. [14] demonstrated that the implementation of PjBL supported by TPACK can increase student activity during learning. These findings indicate that PjBL has potential for developing collaborative skills, while TPACK integration can strengthen the meaningful use of technology in the learning process.

Nevertheless, an important research gap remains to be addressed. Studies on PjBL in elementary mathematics learning tend to examine collaboration or communication skills separately, whereas studies integrating PjBL and TPACK have more commonly focused on student activity, engagement, or competencies in general. Thus, research that specifically integrates PjBL and TPACK in elementary mathematics learning to develop students' collaboration and communication skills simultaneously remains limited. This gap concerns not only the simultaneous use of two approaches but also how technology, pedagogical strategies, and mathematical content are designed as an integrated whole throughout each stage of the project.

Based on this gap, the novelty of this study lies in the integration of Project-Based Learning (PjBL) and the Technological Pedagogical Content Knowledge (TPACK) framework specifically within elementary mathematics learning to develop students' collaboration and communication skills simultaneously. Unlike the application of PjBL that primarily emphasizes project activities as a form of student-centered learning, this study integrates TPACK to ensure alignment among mathematical content, pedagogical activities, and technology throughout the project process. This integration is designed to provide students with structured opportunities to collaborate, share responsibilities, discuss mathematical ideas, communicate their reasoning and the processes underlying their solutions, and utilize technology as an integral component of meaningful project completion. Thus, the novelty of this study does not merely lie in the simultaneous use of PjBL and technology but in integrating both through the TPACK framework to establish a clear alignment among mathematics learning objectives, pedagogical strategies, and technology utilization throughout the project.

Based on the foregoing discussion, this study aims to examine the integration of Project-Based Learning and TPACK in improving students' collaboration and communication skills in elementary mathematics learning. The study focuses on creating a learning process that enables students to participate in project activities actively, collaborate with group members, communicate mathematical ideas and reasoning, and utilize technology as an integral part of meaningful learning experiences. Therefore, this study is entitled "Integrating Project-Based Learning and TPACK to Improve Students' Collaboration and Communication Skills in Elementary Mathematics."

2. METHOD

2.1. Research Design

This study employed a Classroom Action Research (CAR) design using the Kemmis and McTaggart model [15]. The CAR approach was selected because it provides a systematic process for identifying learning problems, implementing instructional actions, observing the effects of the actions, and reflecting on the results to improve subsequent learning practices. The study aimed to improve students' collaboration and communication skills in elementary mathematics through the integration of Project-Based Learning (PjBL) and Technological Pedagogical Content Knowledge (TPACK).

The research was conducted in cycles, with each cycle consisting of four stages: planning, action, observation, and reflection. In the planning stage, the researcher prepared the teaching module, learning media, student worksheets, project activities, and observation instruments. In the action stage, mathematics learning was implemented through the integration of PjBL and TPACK. In the observation stage, students' collaboration and communication skills and the implementation of the learning process were systematically observed. In the reflection stage, the results of the observation were analyzed to identify improvements and aspects requiring revision for the subsequent cycle.

The instructional intervention integrated the six stages of PjBL: (1) determining a fundamental question, (2) planning the project, (3) developing a project schedule, (4) monitoring project implementation, (5) assessing the project results, and (6) evaluating the

learning experience. TPACK was integrated throughout the learning process by combining mathematical content, pedagogical strategies, and technology. Technology was used to present contextual learning situations and project instructions through projectors and PowerPoint presentations, while pedagogical strategies included inquiry, cooperative learning, scaffolding, discussion, presentation, peer interaction, and reflection.

The research consisted of a preliminary observation followed by three action cycles. The results of Cycle I were used as a basis for improving the learning process in Cycle II, and the results of Cycle II were used as a basis for improving the learning process in Cycle III. The research was concluded when the predetermined criteria for students' collaboration and communication skills were achieved.

2.2. Participant

The study was conducted in Class IV C of SDS Islam Al-Falah 2 Jambi during the first semester. The participants consisted of 25 fourth-grade students, including 12 male and 13 female students. The study was conducted during mathematics learning activities and involved all students in the class.

The researcher acted as the teacher implementing the instructional intervention, while an observer assisted in documenting the implementation of the learning process and students' collaboration and communication skills.

2.3. Research Procedure

The research procedure followed the Kemmis and McTaggart model consisting of planning, action, observation, and reflection.

During the planning stage, the researcher identified the problems related to students' collaboration and communication during mathematics learning. The researcher then analyzed the curriculum and prepared a teaching module integrating PjBL and TPACK. Learning media, student worksheets, project activities, learning resources, and observation instruments for collaboration and communication were also prepared.

During the action stage, the teacher implemented mathematics learning through the integrated PjBL-TPACK approach. The learning activities consisted of opening, core, and closing activities.

At the beginning of the lesson, the teacher greeted the students, checked attendance and readiness, and conducted an aperception by presenting contextual images or short videos through a projector. The teacher then connected the displayed situation with the mathematical topic and introduced the learning objectives.

The core activities followed the six stages of PjBL. First, the teacher presented a contextual situation and posed a fundamental question related to the mathematical concept. Students were encouraged to respond to the question and express their initial ideas. Second, students were organized into groups and planned the project with guidance from the teacher. The teacher presented the project procedures using PowerPoint and distributed worksheets to guide the students. Third, the teacher and students established a project completion schedule. Fourth, students worked collaboratively to complete the project while the teacher monitored their activities and provided scaffolding when necessary. During this

stage, students were encouraged to exchange ideas, divide responsibilities, listen to their peers, negotiate differences, and contribute to the completion of the project.

Fifth, each group presented its project results to the class. Other students were given opportunities to ask questions, provide responses, and comment on the presented work. This activity provided opportunities for students to practice expressing ideas clearly, explaining information, listening actively, and using appropriate language. Sixth, the teacher and students reflected on the project and the learning experience.

In the observation stage, the observer recorded students' collaboration and communication skills using structured observation sheets. Collaboration was observed through students' cooperation, responsibility, compromise, and contribution during group activities. Communication was observed through students' ability to express ideas or opinions clearly, explain or present information, listen actively, and use appropriate language. Teacher activities during the implementation of the PjBL-TPACK learning process were also observed.

In the reflection stage, the researcher analyzed the observation results and identified the strengths and weaknesses of the learning implementation. The findings were used to determine the necessary improvements for the subsequent cycle. Improvements could include classroom management, group organization, teacher scaffolding, project instructions, opportunities for student participation, and strategies for encouraging students to communicate and collaborate more actively.

2.4. Data Collection

Data were collected through observation, interviews, and documentation. Observation was the primary data collection technique and was used to measure students' collaboration and communication skills during mathematics learning. Observations were conducted during group discussions, project activities, presentations, question-and-answer sessions, and reflection activities.

Interviews were conducted to obtain supporting information regarding the implementation of the integrated PjBL-TPACK approach and students' responses during the learning process. The interviews focused on students' experiences in working with group members, expressing opinions, listening to others, and participating in project activities.

Documentation was used to complement the observation and interview data. Documentation included photographs of learning activities, student worksheets, project results, teaching modules, attendance records, and other relevant documents.

2.5. Instrument

The research instruments consisted of collaboration observation sheets, communication observation sheets, teacher activity observation sheets, interview guidelines, and documentation instruments.

The collaboration observation sheet consisted of four indicators: (1) cooperation, (2) responsibility, (3) compromise, and (4) contribution. Cooperation referred to students' ability to work with group members and support the achievement of common goals.

Responsibility referred to students' ability to carry out assigned roles and complete group tasks. Compromise referred to students' willingness to accept different opinions and reach agreements. Contribution referred to students' active participation in providing ideas and efforts during project activities.

The communication observation sheet consisted of four indicators: (1) expressing ideas or opinions clearly, (2) explaining or presenting information, (3) active listening, and (4) using appropriate language. These indicators were selected to represent students' communication during discussion, project completion, presentation, and interaction with other groups. Both observation instruments used a five-point rating scale, consisting of 5 = very good, 4 = good, 3 = fair, 2 = poor, and 1 = very poor.

The teacher activity observation sheet was used to determine the extent to which the integrated PjBL-TPACK learning process was implemented as planned. The observed aspects included the opening activity, presentation of contextual problems, fundamental questioning, project planning, scheduling, project monitoring, project presentation, evaluation, and closing activities.

2.6. Data Analysis

The data were analyzed using descriptive quantitative and qualitative analysis. Quantitative analysis was used to determine the percentage of students' collaboration and communication skills in each cycle. Qualitative analysis was used to describe students' behaviors, interactions, participation, and changes observed throughout the learning process.

3. ANALYSIS OF COLLABORATION AND COMMUNICATION SKILLS

Students' collaboration and communication skills were analyzed based on the scores obtained from the observation sheets. Each indicator was scored on a scale of 1–5. The percentage of achievement was calculated using the following formula adapted from Purwanto [16]:

$$P = \frac{\sum X}{\sum X_{max}} \times 100\%$$

where P represents the percentage of achievement, $\sum X$ represents the total score obtained, and $\sum X_{max}$ represents the maximum possible score.

The percentage results were interpreted using the following criteria.

Table 1. Criteria for Students' Collaboration and Communication Skills

Percentage	Category
86–100%	Very Good
76–85%	Good
66–75%	Fair
50–65%	Poor
<50%	Very Poor

The improvement in students' collaboration and communication skills was determined by comparing the percentage obtained in each cycle. An increase in the percentage from the previous cycle indicated an improvement in the targeted skills.

The research was considered successful when students demonstrated improvement in both collaboration and communication skills through the implementation of the integrated PjBL-TPACK approach.

The intervention was considered successful when the average percentage of students' collaboration skills and communication skills reached at least 76%, corresponding to the *good* category. In addition to the quantitative criterion, qualitative observations were used to confirm improvements in students' participation, cooperation, responsibility, contribution, ability to reach agreement, expression of ideas, presentation of information, active listening, and appropriate language use. The research was concluded when the predetermined success criteria were achieved, and the implementation of the integrated PjBL-TPACK approach demonstrated a consistent improvement in students' collaboration and communication skills across the action cycles.

4. RESULTS AND DISCUSSION

The research results focus on the development of students' collaboration and communication skills through the implementation of Project-Based Learning (PjBL) integrated with the Technological Pedagogical and Content Knowledge (TPACK) approach in mathematics learning. The research was conducted in three cycles, with each cycle consisting of two meetings. The success indicator was set at 76%.

4.1. Pre-Cycle Condition

Before the implementation of the intervention, observations were conducted to identify students' initial collaboration and communication skills. The results showed that both skills were still relatively low. The students' collaboration skill score was 42.8%, which was categorized as very poor. Meanwhile, their communication skill score was 40.6%, also categorized as very poor. These findings indicated that students still had difficulties working together, sharing responsibilities, contributing to group activities, expressing ideas, explaining information, listening actively, and communicating using appropriate language. Therefore, an instructional intervention integrating PjBL and TPACK was implemented to improve students' collaboration and communication skills.

4.2. Results of Cycle I

In Cycle I, PjBL integrated with TPACK was implemented through project-based mathematics learning activities. Students were encouraged to work in groups, discuss ideas, divide responsibilities, and present the results of their project activities. The observation results showed an improvement in students' collaboration and communication skills compared with the pre-cycle condition. Students' collaboration skills increased to an average of 62.8%, while their communication skills reached an average of 61.6%. Both skills were categorized as poor and had not yet reached the predetermined success indicator of 76%. The improvement indicated that students had begun to participate more

actively in group activities. However, several students were still hesitant to express their opinions, contribute to group tasks, listen actively to their peers, and communicate their ideas clearly. Therefore, further improvement was needed in the following cycle.

4.3. Results of Cycle II

In Cycle II, improvements were made based on the reflection from Cycle I. Learning activities were designed to provide students with greater opportunities to collaborate and communicate during project completion.

The results showed a substantial improvement in both indicators. Students' collaboration skills increased to an average of 76.6%, while communication skills increased to 76.4%. Both indicators reached the good category and exceeded the success criterion of 76%.

The improvement demonstrated that students were becoming more actively involved in group work. They were able to share responsibilities, contribute to project activities, discuss ideas, and communicate information more effectively. Students also demonstrated better listening behavior and greater confidence in expressing their opinions. Although the success indicator had been achieved, the research continued to Cycle III to ensure that the improvement in collaboration and communication skills was consistent and more optimal.

4.4. Results of Cycle III

Cycle III was conducted to strengthen and maintain the improvements achieved in Cycle II. Learning activities continued to emphasize student collaboration, active communication, group responsibility, and project completion through the integration of PjBL and TPACK.

The results showed a further increase in both skills. Students' collaboration skills reached an average of 90.0%, while their communication skills reached an average of 90.2%. Both indicators were categorized as very good and substantially exceeded the success criterion of 76%. At this stage, students demonstrated strong abilities to work cooperatively, take responsibility for group tasks, contribute to project activities, reach agreements, express ideas, explain information, listen actively, and communicate using appropriate language. The results indicated that the implementation of PjBL integrated with TPACK was successful in developing students' collaboration and communication skills.

4.5. Comparison of Students' Collaboration and Communication Skills Across Cycles

The development of students' collaboration and communication skills from the pre-cycle to Cycle III is presented in Table 2.

Table 2. Improvement in Students' Collaboration and Communication Skills across Research Stages

Research Stage	Collaboration (%)	Category	Communication (%)	Category
Pre-Cycle	42.8	Very Poor	40.6	Very Poor
Cycle I	62.8	Poor	61.6	Poor
Cycle II	76.6	Good	76.4	Good
Cycle III	90.0	Very Good	90.2	Very Good

The table shows a consistent improvement in both collaboration and communication skills throughout the research. Collaboration increased from 42.8% in the pre-cycle to 62.8% in Cycle I, 76.6% in Cycle II, and 90.0% in Cycle III. Similarly, communication skills increased from 40.6% in the pre-cycle to 61.6% in Cycle I, 76.4% in Cycle II, and 90.2% in Cycle III.

The improvement in both indicators demonstrates that the implementation of PjBL integrated with TPACK progressively strengthened students' ability to work collaboratively and communicate effectively during mathematics learning. Since both indicators exceeded the 76% success criterion in Cycle II and showed further improvement in Cycle III, the research was concluded after Cycle III.

4.6. Discussion

The research findings indicate that the implementation of Project-Based Learning (PjBL) integrated with Technological Pedagogical and Content Knowledge (TPACK) was able to improve the collaboration and communication skills of Grade IV C students at SDS Islam Al-Falah 2 Jambi in Mathematics learning. The improvement was consistently observed from the pre-cycle condition through Cycle III. Collaboration skills increased from 42.8% in the pre-cycle to 62.8% in Cycle I, 76.6% in Cycle II, and 90.0% in Cycle III. Meanwhile, communication skills increased from 40.6% to 61.6%, 76.4%, and 90.2%, respectively. This pattern indicates that the gradual implementation of the learning approach provided students with opportunities to adapt to learning activities that required group work, task distribution, discussion, problem solving, and project-result presentation. This finding is consistent with Bell [17], who explained that Project-Based Learning provides students with opportunities to develop 21st-century skills through student-centered learning, inquiry activities, collaborative work, technology use, and communication of learning outcomes [18], [19].

The high level of collaboration skills in Cycle III can be explained by the characteristics of PjBL, which directly place students in situations requiring them to work together to achieve a particular product or goal. In the pre-cycle, the collaboration score of 42.8% indicated that students were still accustomed to learning patterns that provided limited opportunities to share responsibilities, compromise, contribute, and complete tasks collectively. After PjBL was implemented, students repeatedly engaged in the process of determining essential questions, planning projects, distributing tasks, developing

schedules, completing projects, presenting the results, and conducting evaluations [20]. These repeated experiences enabled students to understand that project success was determined not only by individual abilities but also by the contribution of every group member. Thus, the increase in collaboration from 42.8% to 90.0% did not occur suddenly but resulted from repeated collaborative practice that became increasingly structured in each cycle.

These findings are further supported by the research of Sholihah et al. [21], who developed PjBL-based science worksheets to improve students' collaboration and communication skills. Their research demonstrated that PjBL can serve as a learning environment that provides students with opportunities to develop both skills through project activities. Similar findings were also reported in research on the implementation of PjBL in Mathematics learning at the elementary school level, which showed an increase in students' collaboration skills following the implementation of project-based learning [22], [23]. Therefore, the collaboration achievement of 90.0% in this study further supports the evidence that PjBL is appropriate for developing elementary school students' ability to work collaboratively, particularly when project activities are systematically designed and implemented continuously.

The improvement in communication skills from 40.6% in the pre-cycle to 90.2% in Cycle III can also be understood in terms of the increasing opportunities students had to interact verbally throughout the learning process. PjBL not only requires students to produce a product but also requires them to discuss ideas, explain solution procedures, express opinions, listen to group members, make decisions collectively, and present project results [24]. At the beginning of the implementation, students were still hesitant to express their opinions and explain their work. However, through repeated activities in Cycles I, II, and III, students gained increasingly intensive communication experiences. Project-result presentations became an important factor because students were not only required to communicate within their groups but also learned to convey information to other groups and respond to questions or feedback.

These findings are consistent with the research of Farokhah et al. [25], which found that project-based learning could improve elementary school students' mathematical communication skills. The study involved 63 elementary school students and compared PjBL with and without the mind-mapping technique; the results showed that the improvement in mathematical communication skills in PjBL using mind mapping was better than that of PjBL without the technique. Other research involving elementary school students has also demonstrated that PjBL is effective in developing mathematical communication because students are provided with opportunities to communicate mathematical ideas and information through project activities [26]. Therefore, the communication achievement of 90.2% in Cycle III can be viewed as a consequence of students' increasingly intensive experiences in expressing ideas, explaining information, listening, and presenting learning outcomes.

In addition to the characteristics of PjBL, the high achievement in Cycle III was also related to the integration of TPACK into the learning process. TPACK emphasizes that technology should not merely be used as an additional component of learning but

should be integrated with pedagogical knowledge and the content being taught. Latip et al. [27] described TPACK as a form of knowledge that integrates technology, pedagogy, and content, allowing technology use to be aligned with pedagogical strategies and the characteristics of learning content. In the context of this study, technology can provide students with media for obtaining information, developing or documenting projects, processing information, and presenting their work [28]. When technology use is incorporated into the PjBL structure, students do not merely use technology individually but employ it as part of the group-work process [29]. This condition can expand opportunities for students to discuss, share information, compare results, and communicate ideas.

The integration of PjBL and TPACK may also explain why the improvement in Cycle III was greater than that in Cycle I. In Cycle I, students were still adapting to the new learning pattern, resulting in collaboration and communication achievements of 62.8% and 61.6%, respectively. After reflection and improvements were made in Cycle II, students were provided with greater opportunities to interact and complete projects collaboratively, resulting in collaboration increasing to 76.6% and communication to 76.4%. Subsequently, Cycle III served to strengthen the skills that had already developed. Experiences from the previous cycles helped students better understand task distribution, group-work rules, ways of expressing opinions, and presentation procedures. Therefore, the improvement in Cycle III to 90.0% for collaboration and 90.2% for communication indicates that repeated learning processes accompanied by reflection can produce more stable skills.

The findings regarding the integration of PjBL and TPACK are also supported by recent research that developed a TPACK-based learning module integrated with PjBL to develop students' 4C skills at the elementary school level [12]. The study specifically positioned communication and collaboration as components of 21st-century skills developed through the integration of TPACK and PjBL. Other research on the implementation of PjBL using the TPACK approach in elementary school IPAS learning also demonstrated that the approach created active and student-centered learning while encouraging students' cooperation and responsibility; the study also reported an average learning outcome of 80.77 with 84.62% classical mastery [30]. These findings strengthen the argument that the combination of a project-based learning model and technology integration supported by pedagogical and content knowledge can create a learning environment conducive to the development of 21st-century skills.

Another factor that contributed to the high achievement in Cycle III was the improvement in teacher activity during the learning process. In PjBL implementation, the teacher does not merely function as a transmitter of knowledge but as a facilitator who guides students in identifying problems, designing projects, distributing tasks, monitoring the process, providing feedback, and conducting reflection. As the teacher's ability to manage the learning stages improved from one cycle to another, the structure of student activities also became clearer. This condition enabled students to receive sufficient support when experiencing difficulties in collaborating or communicating their ideas. Therefore, the improvement in teacher activity can be considered one of the supporting conditions

explaining the consistent improvement in students' collaboration and communication skills [31].

Nevertheless, the relationship between TPACK and learning outcomes needs to be interpreted carefully. TPACK is essentially a framework of teacher knowledge for integrating technology, pedagogy, and content, rather than a learning model that automatically improves learning outcomes. Therefore, in this study, the improvement in collaboration and communication skills is more appropriately explained as the result of the synergy between PjBL as a learning model and TPACK as a framework for integrating technology, pedagogy, and content, rather than as an effect of technology use alone.

The improvement in collaboration and communication skills also occurred alongside an improvement in Mathematics learning outcomes. The mean learning outcome increased from 67.6 in the pre-cycle to 82.32 in Cycle I, while classical mastery increased from 48% to 68%. Although classical mastery in Cycle I had not yet reached the success indicator of 75%, the increase in the mean score indicated initial development following the implementation of the intervention.

Overall, the research findings demonstrate that the high levels of collaboration (90.0%) and communication (90.2%) achieved in Cycle III resulted from a learning process that was gradual, repeated, collaborative, and reflective. PjBL provided an activity structure that directly required students to work together, share responsibilities, discuss, solve problems, and present their results [32]. TPACK supported teachers in integrating technology appropriately with pedagogical strategies and Mathematics content. When both approaches were implemented consistently and improved based on reflection in each cycle, students gained increasingly rich learning experiences, enabling their collaboration and communication skills to develop from very low levels to very good levels. These findings reinforce previous research concerning the effectiveness of PjBL in developing collaboration and communication skills and demonstrate that technology integration through the TPACK framework can support the creation of active Mathematics learning oriented toward 21st-century skills.

5. CONCLUSION

The results of this classroom action research demonstrate that the integration of Project-Based Learning (PjBL) and Technological Pedagogical and Content Knowledge (TPACK) can improve students' collaboration and communication skills in Mathematics learning among Grade IV C students at SDS Islam Al-Falah 2 Jambi. The implementation of PjBL provided students with structured opportunities to work in groups, share responsibilities, discuss mathematical ideas, complete projects, and present their results, while TPACK supported the meaningful integration of technology with pedagogical strategies and Mathematics content.

Students' collaboration and communication skills showed a consistent improvement across the research stages. Collaboration increased from 42.8% in the pre-cycle, categorized as very poor, to 62.8% in Cycle I, 76.6% in Cycle II, and finally 90.0% in Cycle III, categorized as very good. Similarly, communication skills increased from 40.6% in the pre-cycle to 61.6% in Cycle I, 76.4% in Cycle II, and 90.2% in Cycle III.

Both indicators exceeded the predetermined success criterion of 76% in Cycle II and demonstrated further improvement in Cycle III. These findings indicate that the repeated, structured, and reflective implementation of PjBL supported by TPACK provided increasingly meaningful opportunities for students to develop cooperation, responsibility, contribution, compromise, expression of ideas, presentation, active listening, and appropriate communication.

Thus, the integration of PjBL and TPACK can be considered an effective approach for strengthening collaboration and communication skills in elementary Mathematics learning. The findings also indicate that the improvement was not attributable to technology use alone, but rather to the synergy between PjBL as a student-centered learning model and TPACK as a framework for aligning technology, pedagogy, and content. Consistent implementation, teacher facilitation, reflection, and improvement across cycles were important factors in achieving the observed learning gains. Therefore, the PjBL-TPACK integration has potential as an alternative approach for creating active, collaborative, communicative, and technology-supported Mathematics learning oriented toward the development of students' 21st-century skills.

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