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Enhancing Pedagogical Content Knowledge in Mathematics Teachers Through Collaborative Professional Development

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ABSTRACT

Purpose of the study: The purpose of this study is to explore how collaborative professional development programs can enhance the Pedagogical Content Knowledge (PCK) of mathematics teachers, particularly in integrating pedagogy with content, improving teaching strategies, and addressing challenges in the classroom.

Methodology: This study uses a qualitative research design with a case study approach. Data collection tools include in-depth interviews, classroom observations, and document analysis. The participants consist of 20 middle school mathematics teachers. Data analysis is conducted using thematic analysis, with a focus on identifying patterns and themes related to the development of PCK.

Main Findings: The study found that collaborative professional development significantly improved teachers' ability to integrate pedagogy with content, implement innovative teaching strategies, and develop more structured lesson plans. Additionally, 75% of teachers reported increased student engagement, while 60% faced challenges related to time and resource limitations.

Novelty/Originality of this study: This study provides new insights into the effectiveness of collaborative professional development in enhancing *Pedagogical Content Knowledge* (PCK) among mathematics teachers. It contributes to existing knowledge by demonstrating the impact of collaborative learning on teaching strategies and identifies key challenges, offering valuable implications for future teacher training programs.

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1. INTRODUCTION

Pedagogical Content Knowledge (PCK) is a very important competency for teachers, especially in teaching mathematics [1]-[4]. PCK includes a deep understanding of the subject matter being taught as well as the best way to convey those concepts to students [5]-[7]. However, various studies show that many mathematics teachers still face challenges in integrating pedagogical and content knowledge effectively [8]-[10]. One proposed approach to improving Pedagogical Content Knowledge is through collaborative professional development, where teachers can learn together, share experiences, and obtain constructive feedback [11]-[13].

In the context of mathematics education, teachers often face challenges in conveying abstract concepts to students [14], [15]. For example, many students have difficulty understanding concepts such as algebra or

geometry due to a lack of relevant and structured teaching approaches. Teachers need to understand how to identify these difficulties and design strategies that can help students overcome these obstacles [16]-[18]. Without adequate support, teachers may rely solely on less effective conventional methods. Therefore, the development of pedagogical skills integrated with content becomes very urgent.

Good Pedagogical Content Knowledge not only includes knowledge of the teaching material, but also involves an understanding of how students learn [19]-[21]. Teachers need to know various ways to explain mathematical concepts based on students' ability levels [22]-[24]. This approach includes the use of visual aids, analogies, or simulations to bridge the gap in understanding. This indicates the need for training that focuses on developing Pedagogical Content Knowledge holistically [25], [26].

Collaborative professional development has been recognized as an effective method for improving teacher competencies, including Pedagogical Content Knowledge [27]-[29]. Through collaboration, teachers can share experiences, discuss challenges faced, and jointly seek relevant solutions [10], [30]. In addition, collaborative activities allow teachers to obtain feedback from colleagues, which can enrich their insights into effective teaching practices [31]-[33]. In this context, collaborative professional development serves not only as a learning tool, but also as a medium for building a learning community.

In many countries, collaborative professional development programs have been widely implemented to improve the quality of mathematics teaching [34]-[36]. These programs typically include discussion sessions, workshops, and classroom observations followed by reflection [37]-[39]. Teachers involved in such programs tend to show significant improvements in their teaching skills and ability to understand students' needs [40], [41]. In addition, they also become more confident in facing challenges in class. Thus, collaborative professional development can be considered as a strategic investment in improving the quality of education [27], [42], [43].

While collaborative professional development has many benefits, its success depends largely on the design and implementation of the program [44], [45]. A well-designed program should take into account the specific needs of teachers and the local context in which they teach. In addition, support from schools and other stakeholders is essential to ensure the sustainability of the program [46], [47]. Without adequate support, such programs may have only a limited impact on improving teacher competency.

Gap analysis between previous studies conducted by Delgado-Rebolledo & Zakaryan [48] namely Previous research has focused on the relationship between understanding of mathematical practices and lecturers' PCK, highlighting the importance of practical experience to build effective teaching skills. However, these studies were limited to individual educators at the tertiary level without exploring the process of collaboration or structured professional development. Meanwhile, the current study offers a more applicable approach through collaboration-based professional development. This study not only targets improving mathematics teachers' PCK but also provides a framework for the integration of collective practices oriented towards continuous improvement of teaching quality. Thus, this study fills the gap by expanding the scope from individual to team collaboration, while highlighting practical strategies to strengthen PCK in the context of secondary education.

This study has significant novelty and urgency in the context of mathematics teacher professional development, especially in improving Pedagogical Content Knowledge (PCK). Although many previous studies have highlighted the importance of PCK, this study emphasizes the role of collaborative professional development as a new approach in improving mathematics teachers' pedagogical skills. By focusing on collaboration between teachers, this study offers practical solutions to address the increasingly complex challenges in mathematics teaching. Given the challenges faced by many teachers in effectively integrating content and pedagogy, this study is highly relevant to provide new insights that can enrich teacher training methods and improve the quality of learning in schools.

Based on this background, this study aims to explore how collaborative professional development can improve mathematics teachers' PCK. The focus of this study is on the collaboration process, the results achieved, and the challenges faced during the implementation of the program. It is hoped that the findings of this study can provide significant contributions in designing more effective and sustainable professional development strategies.

2. RESEARCH METHOD

2.1. Type of Research

This study uses a qualitative approach with a case study design. This approach aims to deeply understand the impact of collaborative professional development on improving the Pedagogical Content Knowledge (PCK) of mathematics teachers. Qualitative research was chosen because it is able to explore rich and contextual data through the exploration of the direct experiences of the teachers involved. The case study design allows for a focus on specific phenomena [49]-[51], namely the interaction and dynamics in the professional development program. Data were collected comprehensively through various techniques, including interviews, observations, and document analysis, thus providing a holistic picture of the PCK improvement process [52]-[54]. With this approach, research can produce in-depth and relevant findings for the development of similar training models in the future.

2.2. Research Subjects

The subjects of the study were 20 secondary mathematics teachers in the city of Pare-Pare who participated in a six-month collaborative professional development program. The selection of subjects was carried out using a purposive sampling technique. This technique was chosen to ensure that the subjects had characteristics in accordance with the objectives of the study [55]-[57], namely teachers who have had at least five years of teaching experience and are active in professional development programs. The research subjects came from various schools in urban and rural areas to obtain data variations. In addition, their active involvement in the program was the main criterion in the selection. This approach is expected to provide a representative picture of the effectiveness of collaborative professional development programs.

2.3. Instruments and Data Collection Techniques

The instruments used in this study included in-depth interviews and observation notes. Data collection techniques applied included interviews to explore teachers' experiences and views on the professional development program, observations during the implementation of training sessions and classroom learning practices, and documentation to analyze changes in learning plans before and after participating in the program. By using these techniques, the data obtained can provide in-depth insights into the effectiveness of the program in improving teacher PCK.

The instrument grid used in this study can be seen in the following table:

Table 1. Research Instrument Grid

Aspects Studied	Indicator	Data Collection Techniques
Understanding PCK	Ability to integrate content and pedagogy	Interview, Observation
Implementation of New Strategy	Application of innovative strategies in teaching	Observation, Documentation
Reflection and Evaluation	Feedback on learning practices	Interview, Observation

2.4. Data Analysis Techniques

The data were analyzed using a thematic approach. The analysis process involved several main stages. First, the data were categorized based on the main themes relevant to the research objectives [58], [59]. Next, the data was coded to identify emerging patterns [60]. The coding results were then interpreted in depth to understand how collaborative professional development affects teacher PCK. Data validity was maintained through triangulation techniques, namely by comparing interview results and observations. This approach allows researchers to present valid and reliable findings.

2.5. Research Procedures

The research procedure includes four main stages. In the first stage, namely preparation, the researcher identifies the research subjects, designs the research instruments, and prepares the implementation schedule. The second stage is implementation, where data is collected through interviews, observations, and documentation during the six-month research period. The third stage involves data analysis using a thematic approach to identify relevant patterns and themes. Finally, in the reporting stage, the researcher prepares a report on the research results based on the findings that have been analyzed. With this procedure, it is hoped that the research can provide a comprehensive picture of the impact of the program on improving teacher PCK. The research procedure can be seen in the following figure:

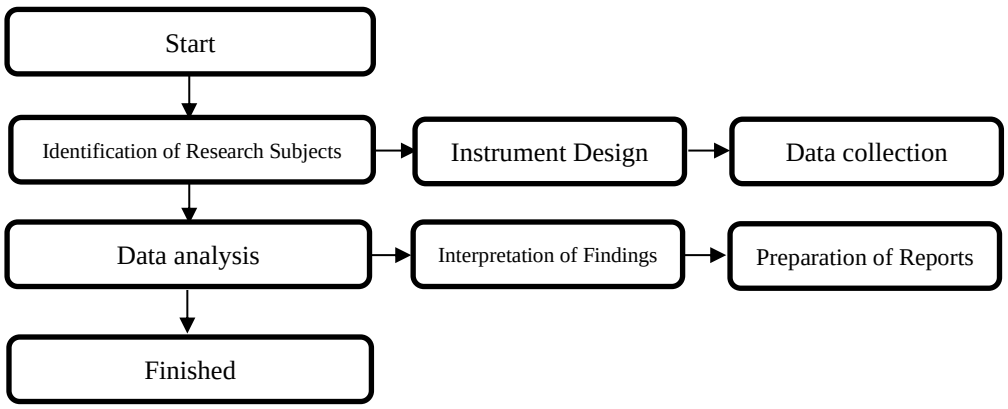

Figure 1. Research Procedure

3. RESULTS AND DISCUSSION

3.1. Interview Results

In-depth interviews were conducted to explore teachers' experiences and views on the collaborative professional development program [61], [62]. The findings showed that the program had a positive impact on teachers' understanding of Pedagogical Content Knowledge (PCK), implementation of new strategies, and reflection and evaluation of teaching practices. However, some challenges such as time and resource constraints were also identified. Details of the interview findings are presented in Table 2 below:

Table 2. Interview Findings

Aspects Studied	Interview Results	Key Findings
Understanding PCK	"I have a better understanding of how to integrate relevant pedagogy and content." – Teacher A "My PCK has improved, especially in explaining geometry." – Teacher B "This program has made me more creative in explaining abstract concepts." – Teacher C "I feel more confident teaching mathematics after this training." – Teacher D "I now understand better how to choose the right method for each concept." – Teacher E "The methods I learned were very helpful in conveying difficult materials." – Teacher F "The use of visual aids was very useful in teaching algebra concepts." – Teacher G "I now pay more attention to how to combine pedagogy and content in my teaching." – Teacher H "This training has changed the way I teach geometry and algebra." – Teacher I "My PCK has improved a lot after learning how to adapt methods to students' needs." – Teacher J "I feel more efficient in designing integrated lesson plans." – Teacher K "More contextual learning is now my focus." – Teacher L "I realize the importance of using a variety of approaches in teaching mathematics." – Teacher M	The program helps teachers understand the integration of pedagogy and content, especially abstract materials such as algebra and geometry.

	"I am better able to design deeper and more meaningful mathematics instruction." – Teacher N "This training taught me how to approach students with various methods." – Teacher O "My PCK is now more complete and comprehensive." – Teacher P "I understand better how to develop students' critical thinking skills through mathematics instruction." – Teacher Q "The methods I learned made me more focused on how students understand concepts." – Teacher R "This training greatly influenced the way I integrate PCK into my learning." – Teacher S "I feel more competent in teaching complex mathematics materials." – Teacher T "I use simulations to clarify difficult concepts." – Teacher A "Small group discussions are very effective in getting students more involved." – Teacher B "Simulations help students understand topics that they previously found difficult." – Teacher C "I introduced project-based methods to improve students' understanding." – Teacher D "The use of visual aids makes it easier for students to understand." – Teacher E "The interactive methods I tried made learning more fun." – Teacher F "I started using video lessons to explain mathematical theories." – Teacher G "My students are more enthusiastic when using interactive tools in learning." – Teacher H	
Implementation of Innovative Strategies		Teachers implement new strategies such as simulations, interactive discussions, and the use of visual aids.

	"I tried problem-based learning techniques, and the results were very positive." – Teacher I "Simulations make it easier for me to explain abstract concepts." – Teacher J "I use digital media to help explain difficult concepts." – Teacher K "Now I integrate group discussions into almost all learning sessions." – Teacher L "This new method helps increase student participation during learning." – Teacher M "I am very impressed with how interactive media makes the material easier for students to understand." – Teacher N "I use contextual and problem-based approaches in learning." – Teacher O "Project-based strategies are very effective in improving students' critical thinking skills." – Teacher P "Students are more interested in learning when I use interesting media." – Teacher Q "I am getting used to using technology in teaching mathematics." – Teacher R "I apply group discussion methods to increase interaction between students." – Teacher S "This new approach has a positive impact on students' understanding of concepts." – Teacher T "Peer feedback really helped me improve my teaching techniques." – Teacher A	
Reflection and Evaluation	"I learned to be more open to constructive criticism from my peers." – Teacher B "After receiving feedback, I tried to improve the way I explained concepts." – Teacher C	Peer feedback encourages teachers to evaluate and improve their teaching methods.

"Peer feedback provided many new perspectives that enriched my methods." – Teacher D

"Positive feedback from peers encouraged me to continue innovating." – Teacher E

"I feel more confident with the feedback I received from my peers." – Teacher F

"Peer feedback inspired me to try other methods." – Teacher G

"Reflecting on my teaching made me aware of many things that need improvement." – Teacher H

"I am more thorough in evaluating each lesson after receiving feedback." – Teacher I

"Peer evaluations help me to focus more on aspects that need improvement." – Teacher J

"I learned to improve my teaching based on the results of the reflection." – Teacher K

"Feedback from fellow teachers helps me identify weaknesses in my teaching." – Teacher L

"After receiving criticism, I feel more motivated to change my approach." – Teacher M

"I understand more about the importance of evaluation in improving the quality of learning." – Teacher N

"The feedback I received made me more open to collaborative learning." – Teacher O

"Constructive criticism made me more creative in designing learning materials." – Teacher P

"Feedback from peers improved the way I interact with students." – Teacher Q

"I learned a lot from the reflection I did with my peers." – Teacher R

	"The feedback I received improved the way I delivered the material." – Teacher S "I am more motivated to try new techniques after receiving feedback from peers." – Teacher T "My main challenge is the lack of time to collaborate with colleagues." – Teacher A "We need more training on learning technology." – Teacher B "Limited access to modern tools is the biggest obstacle." – Teacher C "A busy teaching schedule often prevents me from trying new methods." – Teacher D "Resources for implementing technology in learning are still very limited." – Teacher E "I am constrained by the limited time to implement new strategies." – Teacher F "My school lacks access to devices that support digital learning." – Teacher G	
Challenges Faced	"I wish there was more support from the school for the implementation of interactive tools." – Teacher H "Limited internet access makes it difficult for me to use technology in teaching." – Teacher I "The biggest challenge is the lack of time to prepare and modify materials." – Teacher J "Sometimes, I find it difficult to deal with the limited resources available." – Teacher K "I have to be more creative to overcome the limitations of teaching tools." – Teacher L "The limited time outside of teaching hours makes it difficult for me to collaborate." – Teacher M "We need more training in using the latest technology." – Teacher N	Teachers face limited time and resources for implementing new strategies.

	"My school does not provide enough tools to support new methods." – Teacher O
	"I wish there was a special time allocation for further training." – Teacher P
	"My main challenge is the limited resources in my school." – Teacher Q
	"I have difficulty getting access to adequate training materials." – Teacher R
	"I feel limited by time and resources to collaborate further." – Teacher S
	"The limited budget in the school is a barrier to implementing new methods." – Teacher T

Interviews with 20 mathematics teachers showed that the collaborative professional development program had a positive impact on their understanding of Pedagogical Content Knowledge (PCK). Most teachers felt they had a better understanding of how to integrate pedagogical and content aspects in their learning, especially for abstract materials such as algebra and geometry. They were also more confident in using innovative approaches, such as visual aids and contextual learning methods, which have been shown to help students understand the material better. One teacher stated, “This program has opened my eyes to explaining algebra in a way that is easier for students to understand.”

In addition, teachers reported implementing various innovative learning strategies, including simulations, group discussions, and the use of interactive media. These strategies have been successful in increasing student engagement and helping them understand complex concepts. For example, one teacher stated, “Simulations help students understand topics that they previously found difficult.” Project-based approaches and small group discussions are also favorite strategies for teachers to motivate students to be more active in the learning process.

The program also encourages teachers to reflect and evaluate their teaching methods more often. Peer feedback is considered very helpful in improving teaching techniques. One teacher said, “Input from colleagues really helps me improve my teaching techniques.” This reflection makes teachers more open to constructive criticism and more willing to try new approaches to improve the effectiveness of learning.

However, the interviews also revealed a number of challenges faced by teachers. Limited time to collaborate and lack of access to learning resources, especially in rural schools, were major obstacles. One teacher said, “I have limited time to design new learning media.” This obstacle suggests the need for further support from the school, including specific time allocation for training and access to modern learning technology.

3.2. Observation Results

Observations were conducted for six months on 20 mathematics teachers to monitor their involvement in the collaborative professional development program and the implementation of classroom learning. These observations included activities during training, classroom teaching practices, and analysis of lesson plan documents. The results can be seen in the following table:

Table 3. Observation Results

Aspects Studied	Observation Results	Indicator Kuantitatif
Collaboration During Training	Teachers actively participated in group discussions to share experiences, identify challenges, and design joint learning strategies.	85% of teachers (17 out of 20) actively participated in the discussion.

		70% of teachers (14 out of 20) made significant contributions to the development of learning strategies.
Implementation of New Strategies in Class	Teachers implemented strategies such as interactive simulations, small group discussions, and problem-based learning to increase student participation and understanding.	75% of teachers (15 of 20) used new strategies in the classroom. 65% of teachers (13 of 20) reported an increase in student participation of up to 50%.
Changes in Learning Plans	The lesson plan documents showed significant adjustments, including more specific objectives, problem-based activities, and the use of learning aids.	90% of teachers (18 out of 20) made lesson plans more structured. 80% of teachers (16 out of 20) added visual aids to their lesson plans.
Challenges Faced	Teachers experienced constraints such as limited time to prepare new strategies and lack of access to modern aids, especially in rural schools.	50% of teachers (10 out of 20) reported time constraints as a major constraint. 60% of teachers (12 out of 20) faced challenges in accessing learning resources.

The observation results showed that the collaborative professional development program had a positive impact on the participation and learning practices of mathematics teachers. During the training, 85% of teachers (17 out of 20) actively participated in group discussions, shared experiences, and provided input for the preparation of learning strategies. 70% of teachers (14 out of 20) also made significant contributions in designing innovative strategies that could be applied in the classroom.

The implementation of new strategies in the classroom also showed encouraging progress, with 75% of teachers (15 out of 20) starting to use methods such as interactive simulations, small group discussions, and problem-based learning. As many as 65% of teachers (13 out of 20) reported an increase in student participation of up to 50% after implementing these strategies, especially for complex mathematical concepts.

In terms of lesson planning, 90% of teachers (18 out of 20) made significant changes by creating more structured plans, including the addition of specific objectives and problem-based activities. In addition, 80% of teachers (16 out of 20) started using visual aids in their lesson plans, which were considered effective in helping students understand abstract concepts such as algebra and geometry.

However, the program also faces challenges, especially in terms of time constraints and access to resources. As many as 50% of teachers (10 out of 20) reported that limited time was a major obstacle in preparing new strategies, while 60% of teachers (12 out of 20) expressed difficulties in gaining access to modern learning aids, especially in schools located in rural areas. These constraints indicate the need for further support from schools to ensure the sustainability of the implementation of training outcomes.

The results of this study indicate that the collaborative professional development program significantly improved mathematics teachers' competencies, especially in terms of understanding Pedagogical Content Knowledge (PCK), implementing innovative learning strategies, and planning lessons. This improvement reflects the effectiveness of collaboration-based training, where teachers can share experiences, discuss challenges, and jointly design practical solutions to be implemented in the classroom. This is in line with previous studies showing that collaboration between teachers can enrich pedagogical insights and strengthen the ability to integrate pedagogy with content.

In terms of collaboration during the training, the active involvement of 85% of teachers in discussions indicates that the program has succeeded in creating a supportive learning environment. Group discussions allow teachers to exchange ideas and learn best practices from their peers. This involvement has a positive impact on the development of learning strategies that are more relevant to students' needs. This finding confirms that training based on learning communities can increase teachers' confidence and motivate them to explore new approaches in teaching.

The implementation of innovative strategies in the classroom, such as interactive simulations and problem-based learning, has increased student participation by up to 50% in some classes. These results show that learning methods that actively involve students not only make learning more interesting but also help students understand complex mathematical concepts. The use of interactive simulations, for example, makes it easier for teachers to explain abstract concepts such as algebra and geometry. This proves the importance of relevant learning aids in supporting the teaching and learning process.

Changes in lesson plans were also an indicator of the success of the program. As many as 90% of teachers made significant adjustments by adding more specific objectives and problem-based activities. This shows that the training helped teachers design more focused and outcome-oriented learning. The addition of visual aids by 80% of teachers reflects an awareness of the importance of learning media in bridging the gap in students'

understanding. These adjustments also emphasize that well-designed training can have a direct impact on classroom teaching practices.

However, the study also revealed some barriers that need to be addressed. Limited time to prepare new strategies was reported by 50% of teachers, indicating that teachers' busy work schedules can hinder innovation. In addition, 60% of teachers faced limited access to modern learning tools, especially in rural areas. These barriers highlight the importance of institutional support in providing adequate resources and time for teachers to implement training outcomes. Possible solutions include allocating dedicated time for advanced training and providing technology-based learning tools in schools.

Overall, these findings suggest that collaborative professional development programs can be an effective strategy for improving the quality of mathematics instruction. However, the sustainability of the program's impact requires attention to the barriers faced by teachers. Support from schools, policymakers, and the education community is an important factor in ensuring the successful implementation of training outcomes in the long term.

Findings from previous research conducted by Lara-Alecio et al., [63] supports the findings of this study. Where the study stated that there was a significant increase in teacher knowledge after completing the program. In addition, research conducted by Smith et al., [12] found that teacher professional learning is effective in improving and maintaining the implementation of professional development content among teachers.

This study has a positive impact on mathematics teachers' understanding and teaching practices, by showing that collaborative professional development can improve teachers' Pedagogical Content Knowledge (PCK) and ability to implement innovative learning strategies. This has the potential to improve the quality of mathematics learning and student engagement. However, this study has several limitations, including the limited sample size of 20 teachers in one particular area, which limits the generalizability of the findings. In addition, time and resource constraints in some schools are also factors that affect the implementation of training results, so these findings need to be studied further in a broader context and with more diverse samples.

4. CONCLUSION

Collaborative professional development programs have been proven to be effective in improving mathematics teachers' Pedagogical Content Knowledge (PCK), especially in terms of integrating pedagogy and content, implementing innovative learning strategies, and planning more structured lessons. Teachers who participated in the program showed improved skills in designing problem-based learning, using visual aids, and implementing interactive methods such as simulations and small group discussions, which significantly increased student participation and understanding. However, several obstacles, such as limited time and access to learning resources, remain challenges that need to be overcome. Therefore, support from schools and stakeholders is needed to ensure the sustainability and success of the implementation of the training results. Such programs can be a strategic step in improving the quality of teaching and student learning outcomes sustainably. For further research, it is recommended to expand the sample and cover different regions and school contexts, as well as explore the long-term effects of collaborative professional development programs on improving the quality of teaching and student learning outcomes.

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