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Effectiveness of hybrid project-based learning with digital portfolios in enhancing mathematics pedagogical content knowledge

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Abstract. This study investigates the effect of the Hybrid Project-Based Learning (PjBL) model integrated with digital portfolios on the enhancement of Mathematics Pedagogical Content Knowledge (MPCK) among primary teacher education students. The urgency of this research stems from the persistent gap in teacher education, where traditional methods inadequately develop MPCK in prospective teachers. The main objective was to examine whether the hybrid PjBL model, which combines project-based learning and digital tools, can significantly improve MPCK in primary teacher education students. The research uses a quasi-experimental design with a posttest-only control group. The population consists of primary teacher education students, with a purposive sampling technique used to select two regular classes, each comprising 32 students. The experimental group was exposed to hybrid PjBL, while the control group followed conventional teaching methods. Data were collected using the MPCK scale, a 40-item instrument designed to assess students' mathematical pedagogical competencies. Data analysis was conducted using an independent sample t-test after ensuring normality and homogeneity of variance. The results indicated that the experimental group achieved significantly higher MPCK scores, demonstrating the effectiveness of the hybrid PjBL model in enhancing MPCK. Based on these findings, it is recommended that teacher education programs integrate hybrid PjBL models with digital portfolios to improve MPCK development among prospective teachers.

Introduction

Mathematics is an important foundation in elementary education because it plays a role in shaping students' logical, systematic, and critical thinking skills. The success of mathematics learning in elementary schools is primarily determined by the quality of teachers in delivering material conceptually and contextually. In this case, Mathematics Pedagogical Content Knowledge (MPCK) plays a strategic role. MPCK is a combination of understanding mathematical content and pedagogical strategies that enable teachers to bridge the gap between teaching materials and student characteristics (Loewenberg Ball et al., 2008). Teachers with good mastery of MPCK can identify student misconceptions, choose appropriate instructional approaches, and guide students to achieve deep and sustainable conceptual understanding (Gess-Newsome et al., 2019; Kleickmann et al., 2013; Yilmaz & Demir, 2021).

However, various studies have shown that the mastery of Mathematics Pedagogical Content Knowledge (MPCK) among student teachers, particularly primary teacher education students,

remains inadequate. One study showed that prospective elementary school teachers often describe the teaching and learning of fractions only at the general pedagogical level without distinguishing students' specific difficulties or the core content that must be understood, indicating a shallow understanding of MPCK (Tossavainen, 2024). Another study that examined prospective mathematics teachers' understanding of the concept of limits also found significant shortcomings, where participants had difficulty identifying the roots of students' errors and were only able to provide general learning strategies (Aliustaoğlu & Tuna, 2021; Widana et al., 2024). Meanwhile, a study of secondary school mathematics teachers in Dammam and Khobar showed that their average mastery of MPCK was at a moderate level, with an overall average score of 2.974 out of 5 (Alotaibi & Yousse, 2023), indicating that although not completely low, there is still significant room for improvement. At the research location, many prospective teachers struggle to develop a deep understanding of the mathematical content and the pedagogical strategies required to teach it effectively. Based on the observation of the learning outcomes of primary teacher education students in the Mathematics Education in Lower Primary School course (*Pendidikan Matematika di Kelas Rendah*) during the second semester of the 2023/2024 academic year, the results of the midterm examination and final examination are presented in Table 1. The data reveals significant issues regarding the students' academic performance.

Table 1. Descriptive Statistics of midterm examination and final examination Scores of *Primary Teacher Education* Students

Statistical Measure	Midterm Examination	Final Examination
Number of Data	160	160
Mean	44	55.5
Median	40	55
Mode	30	50
Standard Deviation	16.65	11.76
Maximum	100	80
Minimum	10	23

From the data presented, it can be observed that the average midterm examination score is 44, and the average final examination score is 55.5, indicating that the majority of students have not met the expected performance standards. Additionally, the median scores for the midterm and final examinations are 40 and 55, respectively, further emphasizing that the middle value of student performance is still relatively low, particularly for the midterm examination. The mode values of 30 for the midterm examination and 50 for the final examination indicate that these scores were the most frequently obtained by students, which is below the expected level of achievement.

These results reveal a critical issue at the research location: the low level of academic achievement among primary teacher education students in this course. This suggests a struggle in mastering the course content, as evidenced by the low average and the wide spread of scores. Such outcomes indicate that traditional teaching methods may not be sufficient in helping students achieve the desired learning outcomes. Therefore, there is an urgent need for improved instructional strategies that can address the varying levels of understanding and engagement among the students. These findings highlight a significant gap between the professional demands of teachers in understanding and teaching mathematical concepts in depth and the actual competence of prospective students in mastering MPCK comprehensively.

This gap is a significant challenge in teacher education. Without proper intervention, the limited mastery of MPCK in student teachers can have an impact on the low quality of mathematics learning in elementary schools. This problem is not only related to the aspect of content mastery but also to the inappropriateness of learning methods, the inability to understand students'

thinking, and the difficulty in developing adaptive learning strategies (Aliustaoğlu & Tuna, 2021; Prabowo et al., 2022; Sulastri, 2019). In this context, learning strategies that can foster students' pedagogical and reflective skills are an urgent need in teacher education programs.

One strategy that is recognized as effective is the Project-Based Learning (PjBL) model. This model places students in real problem-based learning situations that require them to think critically, creatively, and collaboratively. PjBL has been shown to improve conceptual understanding and problem-solving skills (Jameson et al., 2023; Klang et al., 2021; Miller & Krajcik, 2019). Along with the development of educational technology, this model can be integrated with digital portfolios, which allow students to systematically record their learning process, reflect, and receive continuous formative feedback (Espinel-Rubio et al., 2021; Guo, 2022; Yang et al., 2023; Jatmika et al., 2025). Research by Maryono et al. (2017) & Pratama et al (2024) show that the use of technology can strengthen students' conceptual understanding through appropriate learning strategies.

In addition, the peer teaching and lesson study approaches have also been widely studied as strategies for developing MPCK. Gladys et al. (2024) research shows that although students have an understanding of mathematical content, they are weak in understanding student characteristics and choosing appropriate strategies. Baki & Arslan (2023) study found that involvement in *lesson study* can strengthen students' pedagogical readiness through a systematic reflective cycle. Both approaches underline the importance of integrating content and pedagogy in the context of direct and collaborative practice. However, these approaches have not fully accommodated aspects of documentation, formative assessment, and technology-based independent reflection.

Therefore, this study offers a more comprehensive approach through a hybrid Project-Based Learning model based on digital portfolios. The novelty of this study lies in the integration of active project-based learning and digital portfolios as a documentation and reflection tool. Unlike peer teaching or lesson study, which focus on practice or observation only, this hybrid approach provides a comprehensive learning experience that includes planning, implementation, documentation, reflection, and assessment in one integrated series. The hybrid PjBL model combines the benefits of project-based learning, where students engage in real-world, problem-solving tasks, with digital tools that support reflective learning and collaboration. In this model, students work collaboratively on projects that require them to integrate both mathematical content and pedagogical strategies. The learning steps include problem orientation, concept exploration, solution collaboration, product development, progress monitoring, and final product evaluation (Montrezor & Passos, 2024). This model encourages critical thinking, collaboration, and reflection, which are crucial for developing MPCK in pre-service teachers. However, the model also presents some limitations, such as the need for careful management of resources and the potential challenges related to digital literacy and technology infrastructure in educational settings (Chávez Ávila, 2017; Martínez-Monterrubio et al., 2024).

In comparison, the conventional teaching methods typically used at the research location involve lectures and textbook-based learning, which often fail to engage students actively or foster a deep understanding of pedagogical content knowledge. These traditional methods emphasize content delivery without significant opportunities for reflective practice or collaborative problem-solving, making it challenging to enhance MPCK effectively. A key component of this study is the integration of digital portfolios. Digital portfolios, or e-portfolios, are collections of digital artifacts that allow students to document their learning journey and reflect on their development. The use of digital portfolios in education has gained considerable attention for its ability to promote meta-cognitive skills, self-reflection, and personalized learning (Kurniawan & Khukmi, 2023; Zambrano et al., 2023). Digital portfolios offer students the opportunity to track their progress, showcase their achievements, and engage in ongoing reflection, all of which are critical for developing MPCK

(Cabrera-Solano, 2020; Cornejo-Sánchez et al., 2020). Moreover, integrating digital portfolios with project-based learning allows students to document the entire learning process, including planning, implementation, and reflection, thereby reinforcing their pedagogical competencies.

The theoretical basis for digital portfolios is rooted in constructivist and reflective practices. Digital portfolios are designed to facilitate integrative learning, where students connect past and present knowledge to achieve a deeper understanding (Raval, 2024). They also support continuous professional development by encouraging reflection on both the learning process and the outcomes (Chávez Ávila, 2017). The flexibility of digital portfolios allows them to serve as tools for self-assessment, personal growth, and digital literacy development, which are essential in today's education system (Mahardika et al., 2024; Recalde et al., 2023). Table 2 presents the processes that occur in classes taught using the Hybrid Project-based Learning model.

Table 2. Learning Steps Hybrid Project-based Learning

Phase	Student Activities	Class Activities	Activities Through LMS	The Role of Digital Portfolio
1. Problem Orientation	Analyzing elementary school mathematics learning cases given by lecturers	Discuss initial understanding of the case	Accessing cases via LMS	Keeping the initial analysis and initial understanding of the case
2. Concept Exploration	Studying relevant mathematical content	Q&A and clarification of content understanding	Reading text materials and watching learning videos	Recording material summaries and reflections on understanding
3. Solution Collaboration	Discuss to design pedagogical solutions	Group discussions and presentations between groups	Online discussion forum with feedback	Save the results of the discussion and the initial draft of the solution
4. Product Development	Developing learning tools and media	Direct consultation with lecturers	Uploading product drafts to the LMS for review	Drafting learning tools and documenting the process
5. Progress Monitoring	Delivering project progress	Oral reports to lecturers periodically	Delivering progress logs via LMS	Record progress and revisions based on lecturer feedback
6. Product Finalization	Complete the learning product	Presentation of project results	Final product collection	Uploading final products and final learning reflections
7. Evaluation & Reflection	Reflecting on the process and results	Evaluation session with lecturers and colleagues	Writing reflections in LMS	Portfolio as evidence of the comprehensive learning process

This Hybrid PjBL model not only equips students with pedagogical content skills but also critical thinking skills, collaborative communication, and reflective thinking. Digital portfolios are the main instrument that bridges individual and collaborative learning processes and integrates online and offline learning experiences harmoniously. Research by Lubna et al. (2024) showed that hybrid learning models involving the use of digital technology showed significant improvements in students' design-thinking skills, creativity, collaboration, and adaptability.

Based on this background, the problem in this study is how the hybrid Project-Based Learning model based on digital portfolios affects the improvement of Mathematics Pedagogical Content

Knowledge of primary teacher education students? The purpose of this study was to test the effectiveness of the model in developing students' pedagogical and content competencies. The hypothesis proposed is that the use of a hybrid PjBL model based on digital portfolios can significantly improve the MPCK of primary teacher education students compared to conventional methods.

Method

This study used a quasi-experimental approach with a posttest-only design with nonequivalent groups. This design was chosen to test the effect of treatment on the experimental group compared to the control group without a pretest. The study was conducted in the primary teacher education program. The population in this study consisted of third-semester students enrolled in the Mathematics Education in Upper Primary School course (*Pendidikan Matematika di Kelas Tinggi*) during the 2024/2025 academic year. These students were distributed across five different classes. Purposive sampling was employed to select two classes with equivalent academic abilities. Academic ability was determined based on students' performance in the previous semester's Mathematics Education in Lower Primary School course, ensuring that both the experimental and control groups were comparable in terms of prior academic achievement. Each selected class comprised 32 students, with one class assigned as the experimental group and the other as the control group. The experimental group received the intervention, which involved a hybrid project-based learning model integrated with digital portfolios, while the control group followed the conventional teaching method. Both groups were taught by the same instructors through team teaching, which ensured consistency in the pedagogical approach and content delivery across both groups.

The learning steps for the experimental group were structured to foster active engagement and reflection. The process began with a problem orientation phase, where students analyzed case studies related to elementary school mathematics problems provided by the instructors. This was followed by the concept exploration phase, where students independently studied relevant mathematical content accessed through an e-learning platform with materials such as text documents and instructional videos. Next, students participated in the solution collaboration phase, during which they worked in groups to design pedagogical solutions to the problems. These collaborative discussions took place both in small groups and through online discussion forums. During the product development phase, students created learning tools and media, such as lesson plans and worksheets, that aligned with the solutions they developed.

The progress monitoring phase involved students reporting their progress regularly to the instructors, who provided feedback and guidance. Finally, during the product finalization phase, students completed their learning products and presented their results, submitting their final products and reflections via the Learning Management System (LMS). The digital portfolio played an essential role in supporting this hybrid project-based learning model. Throughout the learning process, students documented their progress, reflections, and product development in their digital portfolios. The portfolios were used as a tool for continuous formative assessment, allowing students to track their learning journey, reflect on their understanding of mathematical content, and receive feedback from their peers and instructors. In addition to serving as a documentation tool, the digital portfolio encouraged students to engage in self-reflection and self-assessment, fostering metacognitive skills that are crucial for the development of pedagogical content knowledge.

The integration of digital portfolios within the learning model not only facilitated the documentation of students' work but also provided a platform for ongoing reflection, allowing

students to revisit and revise their learning products based on feedback. This process helped enhance the student's ability to critically evaluate their own learning and improve their understanding of the mathematical concepts being taught. The use of the digital portfolio further supported the development of digital literacy as students interacted with various multimedia tools and platforms to organize and present their learning materials.

In terms of internal validity, several measures were implemented to mitigate potential threats. First, purposive sampling was employed to control for selection bias, ensuring that the students in both groups were academically equivalent based on their prior performance in the Mathematics Education in Lower Primary School course course. Additionally, both groups were taught by the same instructors using team teaching, minimizing the risk of confounding variables related to instructor effects. The use of a uniform measurement instrument the MPCK scale across both groups further controlled for instrument-related biases, ensuring consistency and comparability of the data.

To enhance external validity, the study was designed to ensure the findings could be generalized to other educational contexts. Although the study was conducted within a specific university setting, the instructional methods used, which include hybrid project-based learning and digital portfolios, apply to a wide range of educational environments. These methods are effective in various teaching contexts and are not limited to the particular setting of this study. Additionally, since the sample consisted of students from the same cohort, the study was conducted in the primary teacher education program. Programs that were enrolled in the same course are more likely to have findings that are relevant to other similar groups of primary teacher education students.

The data collection instrument used was the MPCK scale, which has been specifically developed to measure the pedagogical competence of mathematics content of prospective elementary school teachers. This scale consists of 40 questions that describe various situations in mathematics teaching practice. Each question has four answer choices, and respondents are asked to choose the answer they consider most appropriate. The MPCK scale includes four subdomains: (1) *Common Content Knowledge* with 15 items, (2) *Specialized Content Knowledge* with 10 items, (3) *Knowledge of Content and Students* with 10 items, and (4) *Knowledge of Content and Teaching* with five items, as presented in Table 3.

Table 3. Framework of MPCK Instrument for Prospective Elementary School Teachers

No	Item subcategories based on MPCK Subdomain	Number of questions
1	Common Content Knowledge - CCK	
1.1	Understanding Mathematical Symbols and Related Notations	5
1.2	Understanding the properties of operations	5
1.3	Solving problems in various ways	5
2	Specialized Content Knowledge - SCK	
2.1	Interpreting student strategies	5
2.2	Naming the types of story problems	5
3	Knowledge of Content and Students - KCS	
3.1	Student misconceptions	5
3.2	Relative difficulty of the problem	5
4	Knowledge of Content and Teaching - KCT	
4.1	Selecting story problems for specific instructional purposes	5
Total Question Items		40

Before being used in the main data collection, this instrument was consulted with a panel of experts in the fields of curriculum, mathematics teaching methods, and educational measurement and

evaluation. Several revisions were made based on the panel's input. Furthermore, the instrument trial was conducted on a random sample of 30 primary teacher education students outside the leading sample group. The reliability of the instrument was calculated using Cronbach's Alpha coefficient of 0.982, while the average item validity reached 0.763. Both values indicate high instrument quality.

The post-test data were analyzed using Jamovi statistical software. Before the hypothesis test was conducted, the data were first tested for normality to ensure that the data distribution followed a standard curve and tested for homogeneity to ensure equality of variance between groups. After both prerequisites were met, the hypothesis test was conducted using an independent sample t-test to determine whether there was a significant difference between the experimental group and the control group in terms of MPCK achievement.

The criteria for concluding this study are based on the significance value (p-value) of the t-test results. If $p < 0.05$, it is concluded that there is a significant difference between the control and experimental groups. Data interpretation is also based on a comparison of the average scores of each MPCK subdomain to provide a more detailed understanding of the influence of learning models on each aspect of the pedagogical competence of mathematical content.

Results and Discussion

This study aims to examine the effect of the hybrid Project-Based Learning model based on digital portfolios on improving the Mathematics Pedagogical Content Knowledge (MPCK) of primary teacher education students. Data collection was carried out through the implementation of a post-test after the learning intervention in each group. The post-test score reflects the level of achievement of students' MPCK both in the experimental group that received hybrid PjBL treatment and the control group that followed conventional learning. The results of the MPCK post-test are presented in Table 4.

Table 4. Descriptives Statistics

	Groups	Posttest_Score
N	Control Group	32
	experimental group	32
Mean	Control Group	71.0
	experimental group	88.2
Median	Control Group	70.0
	experimental group	90.0
Standard deviation	Control Group	10.7
	experimental group	8.62
Minimum	Control Group	50.0
	experimental group	67.5
Maximum	Control Group	97.5
	experimental group	100

Based on the results of the descriptive statistical analysis presented in Table 4, it is known that the average (mean) post-test score of students in the experimental group reached 88.2, with a median value of 90 and a standard deviation of 8.62. Meanwhile, in the control group, the average post-test score was 71.0, with a median value of 70 and a standard deviation of 10.7. The range of scores obtained also showed quite striking differences, with the minimum and maximum scores of each group being 67.5–100 for the experimental group and 50–97.5 for the control group.

The differences in the mean and distribution of these data indicate that students in the experimental group not only have a higher average MPCK achievement but also a more consistent distribution of scores than the control group. These findings provide an initial indication that the use of a digital portfolio-based PjBL hybrid model has the potential to have a positive impact on primary teacher education students' mastery of MPCK.

Before conducting hypothesis testing using the *independent sample t-test*, an assumption test was first conducted, including a normality test and a homogeneity of variance test. This assumption test aims to ensure that the data meets the criteria for normal distribution and has homogeneous variance between groups, which is the main requirement in implementing the independent two-sample t-test. The results of the normality and homogeneity test analysis are shown in Table 5.

Table 5. Tests of Normality

		statistics	p
Posttest_Score	Shapiro Wilk	0.983	0.542
	Kolmogorov-Smirnov	0.0778	0.833
	Anderson-Darling	0.335	0.502

Note. Additional results provided by *more tests*

The results of the normality test were obtained through three methods, as in Table *5*, namely Shapiro-Wilk, Kolmogorov-Smirnov, and Anderson-Darling. Based on the results shown in the Normality Test Table, the significance value (p) of each method is 0.542 (Shapiro-Wilk), 0.833 (Kolmogorov-Smirnov), and 0.502 (Anderson-Darling). Since all p values are greater than 0.05, it can be concluded that the post-test score data in both groups are normally distributed.

Table 6. Homogeneity of Variances Tests

		F	df	df2	p
Posttest_Score	Levene's	1.78	1	62	0.187
	Variance ratio	1.54	31	31	0.238

Note. Additional results provided by *more tests*

Furthermore, to test the homogeneity of variance between groups, Levene's test and the variance ratio were used. Table 6 in the Homogeneity Test shows that the significance value in the Levene's test is 0.187, and the p-value in the variance ratio is 0.238. Both values are also above the threshold of 0.05, so it can be concluded that the variance between the experimental and control groups is homogeneous.

Based on the results of the assumption test, namely the fulfillment of the assumptions of normality and homogeneity of variance, the analysis can be continued using the independent sample t-test to test the hypothesis regarding the difference in MPCK scores between the experimental group and the control group.

The t-test was used to determine whether there was a statistically significant difference between the post-test scores of MPCK students in the experimental group and the control group. The experimental group consisted of students who participated in learning with a hybrid Project-Based Learning model based on a digital portfolio, while the control group participated in conventional learning. The results of the t-test analysis are presented in Table 7 below.

Table 7. Independent Samples T-Test

		Statistics	df	p
Posttest_Score	Student's t	-7.08	62.0	< .001

Note. H_a μ Control Group ≠ μ experimental group

The results of the independent sample t-test presented in Table 7 show a t value of -7.08 with degrees of freedom (df) = 62 and a significance value of $p < 0.001$. A very small p-value (below 0.05) indicates that there is a statistically significant difference between the average MPCK scores of the two groups. Thus, the null hypothesis (H_0), which states that there is no difference between the experimental and control groups, can be rejected. These results indicate that the use of a digital portfolio-based PjBL hybrid model has a significant effect on increasing students' MPCK. This finding is also in line with the results of the previous descriptive analysis, where the experimental group had a higher average score compared to the control group.

The hybrid Project-Based Learning (PjBL) model applied in this study is designed to integrate the strengths of project-based learning with a blended learning system between face-to-face and online (e-learning). The learning process begins with the provision of case studies in the form of real problems that often occur in elementary school mathematics learning. The case is designed to stimulate students' critical thinking and direct them to the need to find contextual and applicable learning solutions. Previous research has shown that the application of PjBL in mathematics learning has succeeded in encouraging students to think more creatively and critically about relevant real problems (Arrieta-Cohen et al., 2024; Fitrah et al., 2025; Ndiung & Menggo, 2024; Rehman et al., 2023), which is very important in developing MPCK. In this case, the use of case studies is an effective first step in building student involvement in solving problems faced in the real world.

After understanding the problem, students access mathematics content materials independently through the e-learning platform. The materials are presented in the form of text and learning videos to accommodate various learning styles, this learning process not only encourages independent learning but also strengthens students' mastery of (Guerrero-Villar et al., 2023) content knowledge. This is in accordance with several research findings, which show that the use of LMS and learning videos in Hybrid PjBL increases the effectiveness of conceptual understanding and encourages independent learning (Guerrero-Villar et al., 2023; Laparra et al., 2023). By giving students the opportunity to access materials flexibly, students can manage their own time and deepen their understanding through relevant materials.

Next, students conduct collaborative discussions both in small groups and between groups, both through online forums and offline during face-to-face sessions. These discussions are directed at

dissecting problems, elaborating content, and designing appropriate pedagogical solutions. Students then compile the final product in the form of elementary school mathematics learning tools that include lesson plans, worksheets, and learning media designed to solve the problems that have been analyzed. The research findings (Montrezor & Passos, 2024; Widana & Laksitasari, 2023) support the importance of collaborative discussions in PjBL, which allows students to exchange ideas and enrich their insights in designing solutions to the problems given. These discussions also build communication and teamwork skills that are very relevant to the needs of collaborative mathematics teaching.

During the face-to-face sessions, the lecturer acts as a facilitator and mentor who monitors the progress of each group's project, provides feedback, and stimulates student reflection on the product being developed. All project outputs and developments are documented by students in the form of a digital portfolio. This portfolio is uploaded periodically to the Learning Management System used in learning. The digital portfolio functions not only as a documentation tool but also as a medium for reflection, formative assessment, and a means to assess the process and results of student learning holistically. The use of digital portfolios in project-based learning is also emphasized in research by (Alfaro et al., 2019), which shows that digital portfolios provide opportunities for students to document their progress in a structured manner, as well as to reflect on their learning outcomes and processes, which ultimately strengthens the development of MPCK.

The results of this study indicate that the hybrid Project-Based Learning (PjBL) model based on digital portfolios can significantly improve the Mathematics Pedagogical Content Knowledge (MPCK) of primary teacher education students. This finding is in line with research (Umboh et al., 2025), which also revealed that the application of the PjBL model in mathematics learning is effective in improving students' mastery of content and pedagogical skills. The integration of project-based learning and e-learning is able to encourage active student involvement and encourage them to produce products that are relevant to real-world problems. The use of digital portfolios in the hybrid PjBL model provides an opportunity for students to reflect on their learning process and outcomes, which also serves as a tool to assess the progress of MPCK mastery.

Furthermore, the research findings by Winarso et al. (2024) showed that learning in a blended learning environment, which combines face-to-face and online learning, greatly supports the development of mathematics teacher competencies. The same thing was seen in this study, where students in the experimental group who implemented Hybrid PjBL showed a significant increase in mastery of MPCK, especially in terms of understanding content and implementing learning strategies that are appropriate to student characteristics. Thus, the results of this study strengthen the argument that project-based learning that combines face-to-face and e-learning can improve the quality of mathematics learning for prospective elementary school teachers.

This finding is in line with research by Lavonen et al. (2023) showing that Project-Based Learning models that integrate the use of digital tools not only increase student engagement but also support the achievement of better learning outcomes, especially in the learning of advanced physics concepts. In this case, the use of digital portfolios in the Hybrid PjBL model allows students to reflect more deeply on their learning and document their progress, which in turn improves the understanding and application of MPCK.

In addition, this finding is also in line with research by Gunaryati et al. (2019), which states that the Learning Management System (LMS) plays an important role in hybrid learning to support the process of knowledge transfer and collaboration between students and lecturers. The use of LMS in hybrid learning allows students to access materials flexibly and collaborate in online discussions,

which in turn supports the development of their pedagogical skills. In this study, the use of LMS to manage projects and document progress through digital portfolios provides a structured learning experience, makes it easier for students to plan and develop more effective learning tools, and integrates technology into the learning process.

Research by Rau et al. (2019) also showed that motivational factors play a significant role in the effectiveness of LMS usage. In this study, e-learning modules that show individual learning progress were proven to be effective in motivating students to learn. Similar findings were found in this study, where digital portfolios uploaded via LMS provide students with the opportunity to track their progress, as well as increase their engagement in the learning process. Digital portfolios serve as documentation and reflection tools, allowing students to identify and address challenges they face during project development.

Furthermore, the results of the study by Setiawan et al. (2022) & Sukendra et al. (2023) showing that the implementation of the hybrid learning model can improve learning performance by supporting the adoption of information technology, which also supports our findings. In this study, the use of technology in Hybrid PjBL not only strengthens students' mastery of MPCK but also helps them develop digital literacy skills that are much needed in the 21st-century education era. This shows that the success of the hybrid learning model is highly dependent on effective technology adoption, as well as the ability of lecturers to manage learning using digital tools that support student engagement.

Another relevant study by Rorimpandeya et al. (2019) highlighted how hybrid learning models can improve the learning outcomes of prospective teachers in science education. The results of this study strengthen the argument that the Hybrid PjBL model, based on digital portfolios, not only improves MPCK but also prepares students with better pedagogical skills and is more adaptive to technological changes in education. Therefore, the results of this study emphasize that the integration of technology in project-based learning has great potential to improve the quality of teacher education and prepare them to face the challenges of education in the digital era.

Overall, these findings show consistency between previous research and the current research, confirming that the digital portfolio-based PjBL hybrid model is efficacious in improving the MPCK of pre-service teachers, as well as encouraging active, collaborative, and reflective engagement in the learning process.

The findings in this study provide significant contributions to the development of teacher education theory and practice, especially in the context of improving *Mathematics Pedagogical Content Knowledge* (MPCK) of primary teacher education students through a hybrid Project-Based Learning (Hybrid PjBL) model based on digital portfolios. Scientifically, this study enriches the existing literature on the application of project-based learning models in higher education by adding a new dimension, namely the integration of e-learning and the use of digital portfolios as an integral part of project-based learning. As part of the development of the pedagogical competence of prospective teachers, the use of digital portfolios in Hybrid PjBL not only functions as a documentation tool but also as a means of reflection that helps students to explore further and evaluate their learning process. Thus, this study provides stronger empirical evidence that the integration of learning projects and digital technology can significantly increase MPCK mastery.

These findings also provide new insights into the effectiveness of hybrid learning models in optimizing mathematical and pedagogical understanding, considering that previously, many studies only focused on one aspect of learning, either face-to-face or online-based projects. By combining the two, this study opens up the possibility for further research into the effect of combining various

learning methods on the pedagogical skills of future teachers. In addition, the use of a Learning Management System as a platform to facilitate discussion, collaboration, and collection of project results also contributes to the development of digital learning systems in higher education.

In practical terms, these findings have a significant impact on the implementation of curriculum and learning strategies in teacher education programs. Given that the use of a digital portfolio-based PjBL hybrid model can significantly improve MPCK, the results of this study can be a basis for educational institutions to develop or design curricula that focus more on project-based learning with technology integration. The application of this model will equip students with better pedagogical skills, as well as improve their ability to design and implement contextual and relevant mathematics learning to meet students' needs.

For educators, the implementation of this model demonstrates the importance of integrating technology into traditional learning processes, both to increase student engagement and to support the development of digital literacy skills. On the other hand, for students, this model provides an opportunity to work more independently and collaboratively and strengthens their ability to design and assess learning tools. With a digital portfolio, students can not only document their learning progress but also identify and address their weaknesses in mastering MPCK. Furthermore, the Hybrid PjBL model also provides a clearer picture of how to overcome resource limitations in education. Online learning allows students to access materials flexibly, while face-to-face learning can still maintain direct interaction and guidance from lecturers. Therefore, this study suggests the implementation of the Hybrid PjBL model based on digital portfolios as a practical solution in designing more effective and efficient learning, especially in the ever-growing digital era.

A critical component in the hybrid Project-Based Learning (PjBL) model implemented in this study is the integration of digital portfolios, which played a central role in supporting the development of Mathematics Pedagogical Content Knowledge (MPCK). These portfolios functioned not only as repositories for documenting student projects but also as structured platforms for reflective learning and formative assessment (Espinel-Rubio et al., 2021; Khalid et al., 2021; Syzdykova et al., 2021; Yang et al., 2023). Through continuous documentation, feedback integration, and revision cycles, students were guided to engage in metacognitive processes that enhanced their ability to connect mathematical content with appropriate pedagogical strategies. This reflective engagement enabled students to critically analyze their instructional planning and respond more effectively to the conceptual needs of learners—an essential dimension of MPCK. Furthermore, the digital portfolio served as a medium for synthesizing self-assessment, peer review, and instructor feedback into a cohesive learning experience, promoting deeper pedagogical insight. This dual function of documentation and reflection distinguishes digital portfolios as an instrumental innovation within the hybrid PjBL framework, contributing meaningfully to the development of pedagogical competence in teacher education.

Thus, these findings not only enrich the scientific understanding of project-based learning but also provide practical guidance for educational institutions to implement learning models that are more adaptive, innovative, and relevant to the development of modern educational needs. These findings provide a significant contribution to both the theoretical and practical dimensions of teacher education, particularly in enhancing Mathematics Pedagogical Content Knowledge (MPCK) through an integrated hybrid Project-Based Learning (PjBL) model with digital portfolios. Unlike previous studies that often focused separately on project-based learning, digital tools, or reflective practices, this study uniquely combines all three into a unified and structured learning framework. This integration enables a comprehensive learning process encompassing planning, implementation, documentation, reflection, and assessment an approach rarely explored in previous research.

The novelty of this study lies in demonstrating how digital portfolios can be strategically embedded within hybrid PjBL to foster metacognitive skills, facilitate continuous formative assessment, and promote professional reflection among pre-service teachers. This model not only addresses the gap in pedagogical content integration but also provides an innovative instructional design that aligns with the demands of 21st-century teacher education. As such, the findings advance current knowledge by validating a scalable and contextually relevant learning approach that supports both pedagogical and technological competence, a contribution that distinguishes this study within the existing body of educational research.

Conclusion

The implementation of a hybrid Project-Based Learning model integrated with digital portfolios has proven to be an effective pedagogical approach in enhancing the Mathematics Pedagogical Content Knowledge (MPCK) of prospective elementary school teachers. By engaging in collaborative, reflective, and contextual learning experiences, students were better equipped to connect mathematical content with appropriate teaching strategies. This model provides a structured framework that not only supports conceptual understanding but also fosters pedagogical reasoning and self-regulated learning. Theoretically, this study contributes to the growing body of knowledge on technology-enhanced teacher education by highlighting the synergy between project-based learning and digital portfolio integration in developing pedagogical competencies. Empirically, it offers a viable instructional model for teacher education institutions aiming to improve MPCK and digital literacy simultaneously. Future research is recommended to explore the scalability of this model across diverse educational settings and its long-term impact on teaching practices.

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