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Original Article

TPACK Mastery through STEM-Integrated Project-Based Learning in Online Physics Course

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Abstract: This study investigates the effectiveness of STEM-integrated project-based learning (PBL) in enhancing prospective physics teachers' TPACK mastery within an online multimedia physics course. Employing a mixed-methods embedded design, 18 prospective physics teachers at Universitas Islam Negeri Antasari Banjarmasin engaged in a five-stage STEM-PBL framework reflection, research, discovery, application, and communication via a learning management system, culminating in educational video projects and lesson plans assessed using a validated TPACK rubric. Descriptive analysis revealed that the majority of students (67.1%) attained moderate TPACK proficiency, with 16.7% achieving high and 22.2% low categories. Although female students demonstrated marginally higher mean scores (M = 82.1) compared to males (M = 81.8), Mann-Whitney tests confirmed no statistically significant gender differences across any TPACK dimension ($p > 0.05$). These findings contribute empirical evidence that STEM-integrated PBL delivered through online platforms effectively fosters technological, pedagogical, and content competencies among prospective teachers, addressing the growing demand for digitally competent educators. The study underscores the pedagogical value of structured, project-based approaches in teacher preparation programs and offers practical implications for designing online learning environments that integrate STEM principles to develop 21st-century teaching competencies.

Keywords :
STEM; Project-Based Learning; TPACK, Gender; Online Physics Instruction

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INTRODUCTION

In this digital era, teachers are tasked with instructing students from a generation that has become deeply entrenched within the digital landscape. Teaching is a skill that requires complex knowledge. Teachers are expected to demonstrate mastery not only of the subject matter, but also of pedagogical methods and technological tools (Putri et al., 2022; Sahin, 2011). The integration of content, pedagogy, and technology in this learning is referred to as Technological Pedagogical and Content Knowledge (TPACK) (Hew et al., 2019; Koehler et al., 2013). Proficiency in TPACK empowers teachers to develop and execute a digital technology-based curriculum, thereby facilitating student learning in the digital era (Canbazoglu Bilici et al., 2016; Niess, 2011). Therefore, it is imperative for prospective teachers to develop a comprehensive understanding of TPACK.

Researchers have developed TPACK assessment instruments (Pamuk et al., 2015; Sahin, 2011; Schmid et al., 2020), explored TPACK mastery among teachers or prospective teachers (Irfan et al., 2018; Juanda et al., 2021; Schmid et al., 2021; Supriyadi et al., 2018), and enhanced TPACK mastery through instruction (Aktaş & Özmen, 2020; Backfisch et al., 2024; Bwalya et al., 2024; Tanak, 2018; Tondeur et al., 2020). It is evident that further research is necessary to enhance TPACK and its implementation among prospective teachers. This phenomenon can be attributed to the persistent challenges associated with the integration and implementation of TPACK. Consequently, further research is necessary to enhance TPACK mastery and practice among prospective teachers. Lachner et al., (2021) conducted a quasi-experimental study comparing classes taught using the TPACK module and control classes not using the module in biology, mathematics, English, German, and philosophy. A quasi-experimental field study involving 208 pre-service teachers across five subjects compared regular courses with and without a three-week subject-specific TPACK module. The results showed that participants who received the TPACK module demonstrated higher TPACK mastery than those in the control group. They also reported greater technology-related self-efficacy and perceived support for technology integration, which contributed to the module's overall effectiveness. The findings indicated that the experimental class, which employed the TPACK module, exhibited superior TPACK mastery in comparison to the control class.

Research by Putri et al., (2020) demonstrated that numeric taxonomy training can enhance the TPACK of biology teachers. This study analyzed instructional videos using an observation sheet covering seven TPACK components: CK, PK, TK, PCK, TCK, TPK, and TPACK. The findings indicated that pre-service teachers generally demonstrated good overall TPACK skills but showed weaknesses in specific components, particularly TPK in both online and offline microteaching and PCK in online settings. The extant research indicates that efforts to develop TPACK through learning strategies and training have a positive effect on the TPACK mastery of both teachers and prospective teachers.The Multimedia Physics Learning course is designed to equip students with the necessary skills and knowledge to develop learning media as part of the integration of digital technology into learning. The course covers various learning media development software and projects, providing students with the opportunity to apply their learning to real-world scenarios. The activities in this course facilitate the implementation of a STEM-integrated project-based learning model.

Project-based learning is a learning model that encourages active student participation in problem-solving through projects (García-Llamas et al., 2025; Nguyen, 2025). Meanwhile, STEM is a learning strategy that integrates Science, Technology, Engineering, and Mathematics (Permanasari, 2016). The integration of STEM education in the curriculum has been shown to foster the development of cognitive abilities in students and to equip them with the necessary skills to utilize technology in problem-solving scenarios (Iskander & Kapila, 2012). A substantial body of research has demonstrated the efficacy of project-based learning (PjBL) and STEM in this regard. PjBL has been demonstrated to enhance soft skills deemed essential in the 21st century, including scientific literacy (Afriana et al., 2016) and creative thinking skills (Anita, 2017). STEM learning can also improve student literacy (Afriana et al., 2016; Subekt et al., 2017), train students' creativity, improve students' critical thinking skills (Hidayati et al., 2019) and encourage students to create something new (Permanasari, 2016). Based on previous research findings, the effectiveness of PjBL and STEM has been widely studied. Despite this, studies that specifically examine the effect of their integration on TPACK in the context of physics learning are still limited. This STEM-integrated project-based learning has the potential to develop TPACK mastery of prospective physics teachers based on the effectiveness of learning in improving several soft skills described previously.

Existing STEM-PjBL research primarily emphasizes improvements in students' cognitive achievement and creativity, whereas TPACK studies tend to focus on technology integration in teaching without explicitly linking it to STEM-based project learning models. As a result, research on online physics learning has predominantly focused on the efficacy of media or learning strategies, with limited attention paid to the integration of these elements in the development of pre-service teachers' TPACK. This study aims describe the implementation of project-based learning integrated with STEM and its impact on students' TPACK mastery in multimedia physics online course.

METHOD

This study employs a mixed-methods approach with an embedded design, adapted from Creswell (2013). The research design is presented in Figure 1.

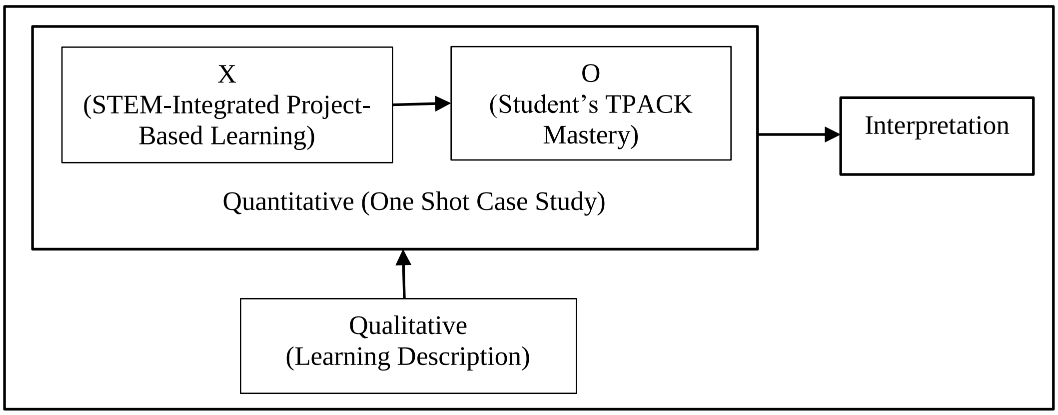

Figure 1. Research Design

Mixed-methods approach with an embedded design is a research design that combines quantitative and qualitative data simultaneously (Öztürk, 2021). where in this study qualitative data is inserted into the quantitative method to provide deeper insights. A quantitative method namely one-shot case studies, were used to measure the TPACK mastery of prospective physics teachers after receiving treatment in the form of integrated STEM project-based learning. The qualitative component served to enrich the quantitative findings by describing the learning implementation and student activities throughout the process. Both sets of data were then interpreted together.

The study involved 18 prospective physics teachers from the Physics Education Study Program at UIN Antasari Banjarmasin who were enrolled in the physics multimedia course. TPACK mastery data were obtained through a performance test evaluated using an assessment rubric for the lesson plan and learning media products created by the students. Performance tests authentically measure knowledge, thus capturing how prospective teachers actually apply TPACK in practice, not just their self-perceptions (Akyuz, 2018; Max et al., 2022). Data on the implementation of STEM-integrated project-based learning were collected through observations using structured observation sheets. The assessment rubric and observation sheets has been validated by 2 experts with very valid results.

Quantitative data analysis focused on the TPACK mastery scores (see Table 1), which were examined using descriptive statistics, including the mean and standard deviation. Additionally, a non-parametric Mann-Whitney test was carried out to identify differences in TPACK mastery between male and female students. Non-parametric statistics were used because of the small sample size, in this study there were 18 people. Qualitative data on the learning implementation were analyzed descriptively and then connected to the main quantitative findings to determine the contribution of the applied learning model.

Table 1. Category of Students' TPACK Mastery

Score	Category
$N \geq 89.31$	High
$74.62 \leq N < 89.31$	Medium
$N < 74.62$	Low

RESULT AND DISCUSSION

STEM-Integrated Project-Based Learning in Online Physics Course

Learning in the digital era demands an approach that focuses on developing 21st-century skills, such as critical thinking (Taqwa et al., 2025), creativity, collaboration, and technological literacy (Sayadi & Pangandaman, 2025). One relevant approach to address these demands is project-based learning (PjBL) integrated with STEM (Oanh & Dang, 2025; Syamra & Suryadi, 2025). The integration of STEM-PjBL in multimedia physics course allows students to learn contextually through solving real-life problems, while connecting cross-disciplinary concepts in a meaningful learning experience. In the context of online physics learning, the STEM-PjBL approach is becoming increasingly important because it can optimize the use of digital technology and encourage student independence and active involvement in the learning process.

The project assigned in the STEM-PjBL learning model in this online physics course involves creating a physics learning video. The project is designed to integrate all four aspects of STEM in an integrated manner. In the science aspect, students apply their understanding of physics concepts and principles, such as laws, formulas, and physical phenomena, which are systematically explained in the learning video. This activity requires students not only to understand the material conceptually but also to be able to represent physics concepts clearly and communicatively so that they are easily understood by the audience. Thus, the learning process does not stop at mastering theory, but continues with the application and transformation of scientific knowledge (Pinar et al., 2025).

In the technology aspect, students utilize various digital applications and software to support the creation of learning videos, such as screen recorders, video editors, and audio devices. This use of technology trains students in digital literacy and technical skills relevant to modern learning needs (Chan & Sung, 2025). Furthermore, in the engineering aspect, students apply scientific and technological principles to design and produce effective learning video products. This includes selecting material presentation methods, screen recording techniques, combining video clips, adjusting sound quality, and developing a flow of material delivery to ensure the video has a systematic and engaging structure. This process reflects the characteristics of engineering, namely designing solutions based on specific needs through stages of planning, testing, and refinement.

Meanwhile, the mathematical aspect is integrated through the use of mathematical calculations in the physics content presented in the learning video. Students present problem solving, data analysis, and mathematical relationships between physics variables accurately and logically. This mathematical integration strengthens students' understanding of the role of mathematics as the language of science, particularly in explaining physical phenomena quantitatively. By integrating the four STEM aspects, this learning aligns with the characteristics of STEM education, which emphasizes interdisciplinary learning through authentic and contextual project-based activities (Kelley & Knowles, 2016; Thibaut et al., 2018).

A study of STEM integration in project-based learning in a multimedia physics course revealed several stages of STEM integration: reflection, discovery, application, and communication (Li et al., 2020). These stages align with the implementation of STEM-PjBL, which is widely used in modern science learning. In this course, learning is designed to be project-based and implemented over four sessions, with each session contributing to the gradual completion of the project. Through this process, students not only produce a product in the form of a physics learning video but also develop conceptual understanding, technical skills, and comprehensive scientific communication skills.

Reflection Stage

The reflection stage is the initial phase of learning designed to encourage students to think critically and reflectively through problem-solving relevant to the learning context. At this stage, students are faced with a problem that requires them to immediately find a solution by linking existing knowledge with the new knowledge they will learn. The reflection stage is implemented during the first meeting as part of the learning orientation, so students have an initial understanding of the direction, goals, and expected competencies during the course.

In this stage, the lecturer acts as a facilitator by presenting authentic problems that are close to learning practices in the field, namely how to design and create effective learning videos. Learning videos are seen as an important medium in modern learning because they are able to bridge the delivery of material visually and audio. Therefore, this stage involves students in formulating solutions aimed at increasing the effectiveness of learning videos in accordance with the principles of project-based learning, which emphasizes contextual and reflective problem solving (Kokotsaki et al., 2016). Students are directed to think about how a learning video can be structured so that the material presented is easily understood by students and can increase their learning motivation. This problem encourages students to focus not only on the technical aspects of video production, but also on the pedagogical aspects that underlie the learning process. Through discussion and reflection, students demonstrated that creating effective learning videos requires skills in systematically organizing learning content. This content development includes clear learning planning, from formulating learning objectives and selecting essential materials to organizing the flow of presentation. Furthermore, students recognized the importance of mastering technical skills in using video editing applications to deliver learning messages in an engaging, communicative, and easily understood manner.

In designing instructional videos, students utilize the knowledge they have learned in the previous semester, particularly regarding instructional design and its preparation in the form of a lesson plan. The lesson plan serves as the primary reference in ensuring that the instructional videos they create align with the desired learning objectives. At this stage, students reapply their understanding of selecting learning strategies, models, and methods appropriate to the characteristics of the physics material and the needs of the students (Darling-Hammond et al., 2020). Selecting the right learning approach will influence the way the material is presented in the video, making it more effective and meaningful.

Research Stage

In the research phase of the learning process, the lecturer plays a facilitative role by providing various reference materials and guiding students in collecting information needed to solve the given problem (Roslina et al., 2023). Rather than delivering content directly, the lecturer scaffolds students' inquiry process and supports them in identifying credible and relevant sources. This stage primarily strengthens students' Content Knowledge (CK) through deeper exploration of physics concepts and enhances their Technological Knowledge (TK) as they begin examining digital tools for video production.

To support pedagogical preparation, the lecturer introduces essential materials on lesson plan development and storyboard design. Students also reflect on their prior experience using video editing applications. Figure 2 illustrates the lecturer's initial briefing session, where key project guidelines, examples of instructional videos, and core planning components are presented. This orientation is crucial because it connects pedagogical planning with technical production skills, thereby fostering the integration of Pedagogical Knowledge (PK) and Technological Knowledge (TK), an early foundation of TPACK development.

To further support student learning, the lecturer provides a video tutorial demonstrating the use of the Animaker video editing application, along with several examples of effective learning videos. All learning materials, including tutorials, examples, and presentation slides, are made accessible through the learning management system (LMS). This accessibility allows students to revisit the materials independently whenever they need additional clarification or deeper understanding, thereby promoting self-directed learning and active engagement throughout the research phase. Subsequently, students determine the physics topic for their learning video project. They analyze the selected content, design an instructional approach, and construct a storyboard outlining the sequence and presentation of concepts. These activities explicitly integrate Content Knowledge (CK) with Pedagogical Knowledge (PK), as students must transform physics concepts into teachable formats. Before proceeding, the lecturer explains the assessment criteria to clarify performance expectations and intended learning outcomes, ensuring alignment between project design and evaluation standards.

In developing the learning video, students are given flexibility to choose from various video editing applications according to their preferences and technical skills. Students are required to conduct further research to deepen their understanding of the physics content, determine suitable teaching strategies, and familiarize themselves with the chosen video editing tools. At the end of the session, students are assigned to prepare a lesson plan and a storyboard concept as the initial outputs of the research phase. These tasks are then submitted through the learning management system (Figure 3), serving as a foundation for the subsequent stages of the learning process. These products serve as measurable indicators of students' developing TPACK, particularly their ability to integrate content, pedagogy, and technology in preparation for producing an instructional physics video. The process carried out by lecturers and students conducting academic learning via Google Meet can be seen in Figure 2.

Figure 2. Lecturer and Students Engage in Academic Instruction Via Google Meet.

Figure 2 illustrates the submission process of students' project outputs through the Learning Management System (LMS), which functions not merely as a storage platform but as an integral component of the learning design. The LMS facilitates structured documentation of students' task completion, enables timely feedback from instructors, and supports iterative revision before progressing to the next instructional phase. By organizing submissions systematically, the platform ensures transparency, accountability, and continuity within the project-based learning cycle.

More importantly, the artifacts uploaded in the LMS represent observable evidence of students' developing Technological Pedagogical Content Knowledge (TPACK). Each submitted task reflects how students align physics content with appropriate pedagogical strategies and digital tools prior to producing their instructional physics video. Thus, Figure 3 demonstrates how the LMS mediates both assessment and professional skill development, capturing the integration of content mastery, instructional design thinking, and technological application in a measurable and documented manner.

Figure 3. Learning Management System used in Online Course

Figure 3 illustrates the role of the Learning Management System (LMS) as a structured medium that supports both assessment processes and the development of professional competencies. Through the systematic submission and documentation of student tasks, the LMS enables instructors to monitor progress, provide formative feedback, and evaluate learning outcomes transparently. At the same time, the platform captures tangible evidence of students' ability to integrate physics content knowledge, pedagogical planning, and technological tools in designing instructional products. In this way, Figure 3 highlights how the LMS functions not only as a submission portal but also as a measurable and traceable environment for fostering and assessing the integration of content mastery, instructional design thinking, and technology use.

Discovery Stage

During the discovery stage, students begin to concretize their ideas by determining the learning design and instructional props required to develop an effective learning video. At this stage, students focus on organizing the learning flow, selecting appropriate visual and audio elements, and identifying supporting materials that can enhance the clarity and appeal of the instructional content. The lesson plans and storyboard drafts previously submitted by the students are then reviewed by the lecturer. Through this review process, the lecturer provides constructive feedback and recommendations to help students improve the pedagogical structure, content accuracy, and technical feasibility of their designs (Figure 4). The feedback given during this stage is essential for refining students' work before video production begins (Prilop & Weber, 2023). By incorporating the lecturer's suggestions, students revise their lesson plans and storyboards to ensure alignment between learning objectives, instructional strategies, and the sequence of material presentation. The revised lesson plans and storyboards subsequently function as a comprehensive guide for transforming instructional concepts into a complete learning video. This process supports students in systematically translating theoretical learning designs into practical digital learning media.

Before proceeding to video production, students must determine the most suitable video editing application to support their design. Selecting an appropriate application is a critical step, as it directly affects the technical quality, efficiency, and creativity of the video. After choosing the application, students are expected to develop adequate skills in using it, either through independent exploration or guided practice. In practice, many students prefer mobile-based applications such as KineMaster and CapCut because they are readily available on smartphones and are relatively easy to operate. Meanwhile, some students opt for PC-based applications such as Canva, which offer more comprehensive design features and produce more visually engaging learning videos. This flexibility allows students to adapt the video production process to their technological skills and preferences.

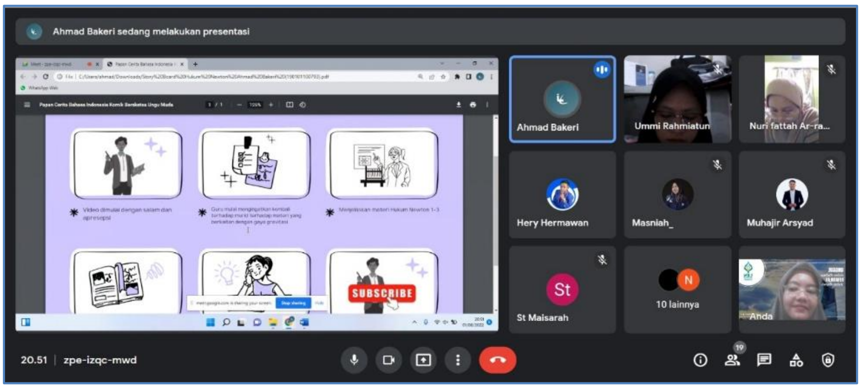

Figure 4. Students Present their Storyboard and Respond to Lecturer Reviews

Application Stage

The application stage is a key stage of learning in which students actively apply the knowledge and skills they have acquired to solve given problems. At this stage, learning emphasizes practical implementation, allowing students to demonstrate their understanding through real tasks. During this meeting, students are required to design lesson plans, develop storyboards, and enhance their proficiency in the video editing applications they have selected. These activities ensure that students are adequately prepared to transform instructional ideas into concrete learning products.

The lesson plans and storyboards function as structured guides that support the systematic development of instructional videos. Through these tools, students align learning objectives with content organization, instructional strategies, and assessment components. Simultaneously, students apply their technical skills by operating video editing applications to present learning materials in an engaging and meaningful way. The ability to integrate visuals, audio, and animations enables students to communicate physics concepts more clearly and effectively.

In addition to video production, this phase encourages collaboration and reflection. Students participate in discussions and share experiences related to the challenges encountered during the video creation process, as well as the solutions they developed to overcome them. This exchange of ideas fosters peer learning, enhances problem-solving abilities (Prilop & Weber, 2023), and strengthens students' confidence in using digital technologies (Monginho et al., 2025).

Communication Stage

The communication phase represents the final stage of STEM-integrated project-based learning, where students share the outcomes of their projects and engage in reflective dialogue. At this stage, students are given the opportunity to present their completed work to the class, allowing them to demonstrate both the learning process and the final product they have developed. As shown in Figure 5, students showcase their instructional videos, which serve as tangible evidence of their ability to integrate content knowledge, pedagogical planning, and technological skills.

During the presentation session, students are encouraged to actively participate by providing constructive feedback on their peers' work. This peer-feedback process helps students develop critical evaluation skills, enhance their communication abilities (Baran et al., 2021), and gain new perspectives on effective instructional design. By observing and commenting on the work of others, students are also able to reflect on the strengths and limitations of their own projects, fostering deeper learning and continuous improvement.

In addition to peer feedback, the lecturer plays an essential role by offering professional feedback on each student's learning video. The feedback focuses on aspects such as content accuracy, clarity of explanation, creativity, instructional effectiveness, and technical quality. This guidance helps students identify areas for improvement and reinforces best practices in developing digital learning media. As a final output, the learning videos produced through the project are uploaded to each student's YouTube account. The video links are then submitted and compiled through the learning management system, ensuring systematic documentation and enabling wider access to student-generated learning resources.

Figure 5. Presentation of Student Work on the Subject of Eyes and Ocular Defects

TPACK Mastery of Prospective Physics Teacher Students

The level of TPACK mastery among prospective physics teacher students who participated in STEM-integrated project-based learning within the Multimedia Physics Learning online course The results of the study indicate that 16.7% of the students demonstrated high TPACK mastery, 67.1% demonstrated medium mastery, and 22.2% demonstrated low mastery (see Figure 6).

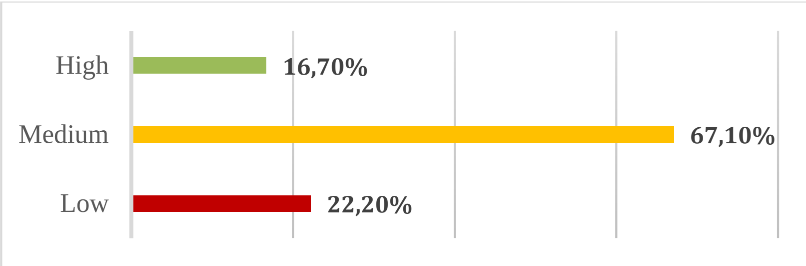

Figure 6. The Level TPACK Mastery of Prospective Physics Teacher Students

This result suggests that the STEM-integrated project-based learning supported moderate development of TPACK mastery but has not yet maximized mastery across all students. The dominance of the medium category indicates emerging integration skills, whereas the proportion of low mastery highlights the need for stronger scaffolding and more intensive practice to achieve higher competency levels. Furthermore, the mastery of TPACK of prospective physics teacher students was analyzed by grouping students according to gender, namely male and female. This categorization was intended to identify potential differences in how male and female students develop and integrate technological, pedagogical, and content knowledge through the implemented learning approach. The overall TPACK achievement of prospective physics teacher candidates is presented in Figure 7, which displays the mean scores obtained by each gender group. The comparison of average scores provides an overview of students' general competency in integrating technology, pedagogy, and physics content. These findings serve as an initial description of gender-based tendencies in TPACK mastery and form the basis for further analysis of each TPACK dimension.

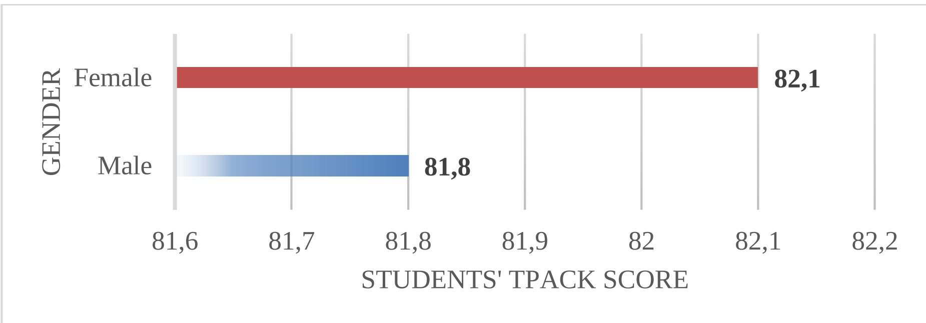

Figure 7. Mean of TPACK Score Prospective Physics Teacher Students by Gender

As illustrated in Figure 2, the average TPACK score of female students (82.1) was slightly higher than that of male students (81.8). This difference indicates a tendency for relatively balanced TPACK mastery between genders, although descriptively, female students showed slightly superior scores. Similar findings were reported by Ergen et al., (2019) who stated that female students often demonstrate stronger pedagogical and reflective skills in designing learning. However, this small difference in scores does not necessarily reflect substantial differences in ability between genders.

The non-parametric statistic Mann–Whitney test results (see Table 2) showed that the difference in TPACK scores between male and female students was not statistically significant ($p = 1.000 > \alpha = 0.05$). This finding confirms the results of previous studies which concluded that gender is not the dominant factor in determining the level of TPACK mastery, but rather learning experience, technology-based pedagogical training, and the intensity of technology use in learning (Schmid et al., 2021).

Table 2. The Result of Mann-Whitney Test

	TPACK Score
Asymp. Sig. (2-tailed)	1.000

A more detailed examination of each TPACK component reveals distinct patterns of competency between male and female students. The findings indicate that male students achieved higher mean scores in several dimensions, namely Technological Knowledge (TK), Content Knowledge (CK), Technological Pedagogical Knowledge (TPK), Pedagogical Content Knowledge (PCK), and overall TPACK, as illustrated in Figure 8. These results suggest that male students tend to demonstrate stronger performance in areas that emphasize mastery of subject matter and the integration of technology within instructional practices. Their higher scores reflect a greater level of confidence in utilizing digital tools, and combining both elements in the learning process.

In contrast, female students exhibited superior performance in the Pedagogical Knowledge (PK) and Technological Content Knowledge (TCK) dimensions. This indicates that female students tend to excel in understanding teaching strategies, classroom management, and the ability to relate technological tools directly to subject content. Their strengths suggest a strong orientation toward instructional design and the meaningful alignment of technology with conceptual understanding, rather than focusing solely on technical proficiency. These tendencies highlight differences in how male and female students approach the integration of pedagogy, content, and technology.

The observed pattern points to differing competency strengths rather than overall disparities in capability. Male students appear to be more confident in the technological and content-related aspects of teaching, while female students demonstrate stronger pedagogical insight and a more nuanced understanding of how technology supports content delivery. These findings are consistent with previous studies (Ergen et al., 2019; Lin et al., 2013; Long et al., 2022; Masry-Herzallah, 2025), which reported that male teachers generally scored higher in technology-related dimensions, such as TK and TPK, compared to female teachers. Such results may indicate that female educators experience lower self-confidence in mastering and operating technology, rather than a lack of actual ability. This underscores the importance of providing equitable learning opportunities and targeted support to enhance technological confidence, particularly for female students, in order to promote balanced development across all TPACK dimensions.

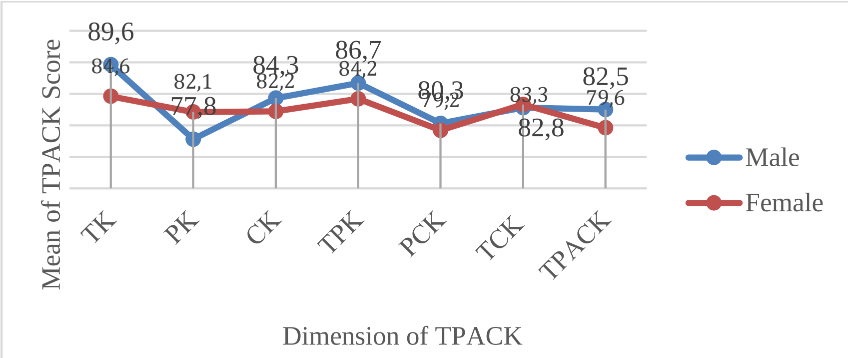

Figure 8. Mean Score of Prospective Physics Teacher Students on Each Dimension by Gender

The figure presents a comparative analysis of the mean TPACK scores between male and female students across seven dimensions: Technological Knowledge (TK), Pedagogical Knowledge (PK), Content Knowledge (CK), Technological Pedagogical Knowledge (TPK), Pedagogical Content Knowledge (PCK), Technological Content Knowledge (TCK), and overall TPACK. Overall, male students demonstrate slightly higher mean scores in most dimensions, particularly in TK (89.6), TPK (86.7), and overall TPACK (82.5), compared to female students, who scored 84.6, 84.2, and 79.6 respectively. In contrast, female students show relatively comparable or marginally higher performance in PK and TCK, indicating a more balanced distribution in pedagogical and integrative knowledge domains. The most pronounced gender difference appears in the TK dimension, whereas differences in other components remain modest. Taken together, the findings suggest that although minor gender-based variations are observable across specific knowledge domains, the overall TPACK profiles of male and female students are largely comparable, reflecting a generally consistent pattern of integrated technological, pedagogical, and content knowledge development.

Although there were differences in mean scores across several dimensions, there was no statistically significant difference (Asymp.Sig. > 0.05) in the TPACK mastery of physics teacher candidates based on gender. This finding is consistent with the research findings of Castéra et al., (2020) which stated that teachers' TPACK perceptions and competencies are more influenced by the educational context, institutional policies, and professional experience, rather than by demographic factors such as gender. Other research also confirms that when access and opportunities for technology training are provided equally, TPACK differences between genders tend to disappear (Scherer et al., 2021). In the context of this study, students had participated in STEM-PjBL-based learning that provided authentic and collaborative experiences in the use of technology, thus potentially minimizing the gender gap in TPACK mastery. This supports the view that inclusive and practice-oriented learning designs can be an effective strategy to reduce disparities in TPACK abilities between genders.

CONCLUSION

STEM-integrated project-based learning implemented in an online physics course was systematically conducted through five interconnected stages: reflection, research, discovery, application, and communication. This structured framework created an authentic and iterative learning environment in which prospective teachers were required to design lesson plans, develop instructional videos, integrate digital tools, and present their work for peer and lecturer feedback. Such experiences provided meaningful opportunities for students to operationalize the interplay between content knowledge, pedagogical strategies, and technological tools, thereby facilitating the development of their Technological Pedagogical Content Knowledge (TPACK). The distribution of TPACK mastery levels indicates that 16.7% of students achieved a high level of mastery, 67.1% demonstrated a moderate level, and 22.2% remained in the low category. These findings suggest that while the intervention effectively supported emerging integrative competencies, further scaffolding is necessary to elevate a greater proportion of students to advanced levels of TPACK proficiency.

Descriptively, female students obtained a slightly higher mean TPACK score (M = 82.1) than male students (M = 81.8). However, the Mann–Whitney test indicated no statistically significant gender differences across any TPACK dimension ($p = 1.00 > \alpha = 0.05$), suggesting that gender does not constitute a determining factor in TPACK development when equitable, technology-rich, and collaborative learning conditions are ensured. Rather, the findings emphasize the importance of high-quality instructional design, authentic project engagement, and systematic feedback in strengthening integrated professional knowledge. Theoretically, this study advances TPACK scholarship by embedding its development within a STEM-integrated project-based online physics learning framework, an area that remains insufficiently explored. Practically, the results demonstrate that well-structured online STEM-PjBL can serve as an effective model for preparing digitally competent and pedagogically adaptive physics teachers. Nevertheless, the limited sample size and one-shot case design warrant caution; future studies should employ larger samples, comparative or quasi-experimental designs, and longitudinal pre–post assessments to establish stronger causal evidence regarding the impact of STEM-integrated project-based learning on TPACK mastery.

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