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Integrating TPACK and collaborative learning to enhance technological proficiency in physics education

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Abstract

This research investigates the role of collaborative learning in enhancing the technological skills of physics teachers. Using the technological pedagogical content knowledge (TPACK) framework, a year-long training program integrated mobile applications into physics education, aiming to boost teachers' technology proficiency and foster team-based teaching methods. Teachers engaged in structured sessions with hands-on activities, collaborative projects, and regular feedback, enabling them to effectively incorporate technology into their lessons. The findings highlight significant advancements in teachers' confidence and competence with mobile apps, creating engaging and impactful learning experiences for students. Moreover, the collaborative nature of the program fostered a professional community among teachers, encouraging ongoing improvement and mutual support. This study underscores the transformative power of integrating technology into physics education when paired with proper resources and collaborative efforts, demonstrating its potential to elevate teaching practices and enhance student learning outcomes. With proper support and resources, teachers can use technology to improve their teaching.

Keywords: TPACK framework, physics education, collaborative teaching, mobile applications, teacher training

INTRODUCTION

In recent years, the integration of technology into education has gained significant attention as a means to enhance both teaching and learning experiences. Particularly in science education, the adoption of digital tools such as mobile applications offer teachers new ways to engage students, facilitate deeper learning, and create interactive learning environments (Zhai et al., 2022). But effectively incorporating these technologies into the classroom requires teachers to have not only access to the tools but also the pedagogical and content knowledge needed for their effective use (Mishra & Koehler, 2006).

The technological pedagogical content knowledge (TPACK) framework provides a comprehensive model for understanding the intersection of technology, pedagogy, and content knowledge in teaching practices (Koehler & Mishra, 2016). By integrating these three components, TPACK emphasizes how teachers can make informed decisions on how to use technology in ways that are pedagogically sound and contextually appropriate. This framework has proven particularly effective in physics education, where the complexity of the content requires thoughtful integration of technology to enhance conceptual understanding (Angeli & Valanides, 2019).

The present study focuses on the application of the TPACK framework to improve the technological skills and collaborative teaching practices of physics teachers in Georgia. Through a year-long professional development (PD) program, teachers were trained to integrate mobile applications into their physics lessons, aiming to foster both individual technological proficiency and collaborative teaching practices. The program involved a combination of hands-on activities, collaborative projects, and continuous feedback to support teachers in effectively utilizing these tools. The study investigates how this training impacted positive changes of teachers' confidence and competence with technology, as well as the development of a professional learning community (PLC) that promoted mutual support and continuous improvement.

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Contribution to the literature

- This study contributes to the literature by demonstrating the effectiveness of the TPACK framework in fostering the technological and pedagogical competencies of physics teachers.
- It highlights how collaborative PD programs, emphasizing the integration of mobile applications, can enhance teachers' confidence, competence, and collaborative practices in using technology.
- Furthermore, the research underscores the importance of creating PLC to support sustainable and ongoing improvements in technology integration within education.

The research also draws upon recent studies that have demonstrated the importance of collaborative learning environments in teacher education, particularly in the context of technology integration (Vongkulluksn & So, 2021). By exploring the impact of this intervention, the study seeks to contribute to the growing body of literature on the role of TPACK in supporting technology integration in physics education (Lee & Tsai, 2020). Furthermore, it aims to highlight the potential of collaborative PD to enhance teaching practices and create sustainable changes in educators' approaches to technology use in the classroom.

The research questions of the present study are as follows:

1. How do physics teachers evaluate the development of their technological competencies and their application in instructional practices following participation in a structured professional training program?
2. What factors in PD process are associated with the successful integration of the digital technologies into the teaching process?

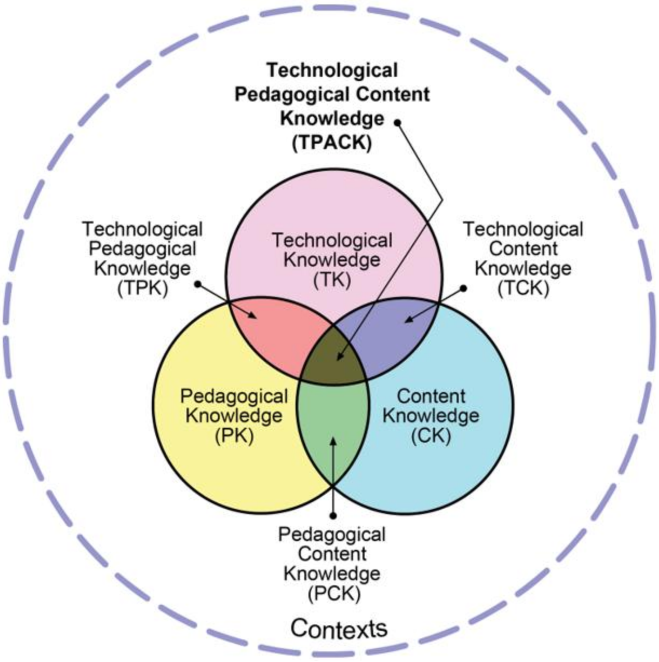

Figure 1. Technological pedagogical content knowledge model (http://tpack.org/)

LITERATURE REVIEW

This research is grounded in the TPACK framework, the integration of technology in science education, and the role of collaborative PD. This chapter will discuss how these elements contribute to effective teaching by exploring the benefits of mobile applications, collaborative PD, and the challenges of technology implementation.

The TPACK Framework

TPACK framework provides a comprehensive model for integrating technology into teaching (Koehler & Mishra, 2016), (**Figure 1**). This framework is particularly crucial for science teachers, who must not only understand their subject matter but also how to teach it effectively using technology. In recent years, TPACK has become a key model in teacher PD, as it helps teachers align technological tools with their pedagogical strategies and the specific content they teach.

The TPACK framework is a dynamic model that emphasizes the interplay between technology, pedagogy, and content knowledge. It suggests that effective teaching requires not just knowledge of the subject matter or technology, but also an understanding of how to integrate technology in a pedagogically sound manner. In physics education, this means using tools like simulations, virtual labs, and interactive whiteboards to create engaging and effective learning experiences (Taşar & Ergül, 2023).

Technology Integration in Science Education

The integration of technology into science education, especially physics education, has become a central focus in recent research on teacher PD. Technological tools, such as mobile applications and simulations, allow students to visualize abstract concepts and engage with physics in interactive and meaningful ways (Sánchez & Barrientos, 2019). The use of mobile applications in particular has shown promise in improving student engagement, motivation, and understanding of physics concepts. According to a study in Lee et al. (2020), mobile technologies provide students with opportunities to explore physical phenomena in dynamic and hands-on ways, which can be particularly helpful for topics that are difficult to visualize or experiment with in traditional classroom settings. For instance, mobile apps that simulate physical experiments or demonstrate real-time interactions with physics concepts–such as force, motion, or energy–help students gain a more intuitive understanding of these ideas (Sánchez & Barrientos, 2019). Additionally, research by Damayanti and Kuswanto (2021) suggests that mobile learning enhances students' problem-solving skills and critical thinking, providing a foundation for deeper learning in physics. Mobile applications are particularly valuable in low-resource settings, as they provide innovative solutions for students who lack access to adequately equipped science laboratories.

Furthermore, mobile applications can provide immediate feedback, an essential feature that supports students in correcting misunderstandings and reinforcing learning (Zhai et al., 2022). This is especially important in physics education, where conceptual misunderstandings can persist if not addressed in real-time.

Mobile Applications in Physics Education

Mobile applications are increasingly being integrated into physics education due to their ability to engage students and support active learning. These applications enable students to interact with physics concepts through simulations, virtual experiments, and real-time data collection. Sánchez and Barrientos (2019) found that mobile apps aid in the visualization of abstract concepts, such as quantum mechanics or electromagnetism, which are challenging to demonstrate in a traditional classroom setting.

Zhai et al. (2022) conducted a meta-analysis which concluded that mobile learning enhances students' academic achievement by offering interactive, flexible, and engaging learning environments. Their research demonstrated that mobile apps allow students to progress at their own pace and revisit concepts as needed, thereby personalizing the learning experience.

A study by Zhai et al. (2020) highlighted the role of mobile technologies in promoting problem-solving skills among physics students. The study found that mobile apps that provide interactive exercises and quizzes enable students to practice physics problems and receive immediate feedback. This reinforcement improves retention and deepens understanding of the concepts (Limniou, 2021)

Mobile applications support the visualization of abstract physics concepts, which can be particularly beneficial for topics that are difficult to visualize or experiment with in traditional classroom settings. Olimovna (2023) highlights the importance of digital educational technologies in enhancing physics education. The study emphasizes that mobile apps offer hands-on experiences and real-time data collection, allowing students to engage more deeply with the material.

Collaborative Professional Development in Technology Integration

Collaborative learning has emerged as a highly effective model for teacher PD particularly in the context of technology integration. Teachers who collaborate in PLCs are more likely to develop the skills and knowledge necessary for effective technology use (Vongkulluksn & So, 2021). PD programs that encourage collaboration enable teachers to share experiences, discuss challenges, and co-create strategies for integrating technology into their teaching practices. According to Fütterer et al. (2019), researchers found that PD programs promoting collaborative learning significantly enhance teachers' confidence in using technology and their ability to incorporate it into their lessons.

The shift towards collaborative PD is supported by studies showing that teachers benefit more from peer learning experiences, where they can exchange ideas and reflect on their teaching practices. Collaborative PD models also provide teachers with ongoing support and feedback, essential for sustaining long-term changes in teaching practices (Chai et al., 2016). For science educators, this model is especially beneficial because it allows teachers to work together to solve common challenges related to integrating technology into their classrooms.

Challenges in Implementing Technology Integration

Despite the benefits of technology integration, several challenges remain, particularly in the context of physics education. One significant barrier is teachers' lack of familiarity with technology and the skills required to effectively incorporate it into their lessons (Pokhrel, 2024). Research by Parker et al. (2019) indicate that many teachers feel unprepared to integrate new technologies, which can lead to resistance to adopting such tools in the classroom. Furthermore, the lack of institutional support, including insufficient resources and training, can hinder the effective use of technology (Shen et al., 2024).

Addressing these challenges requires ongoing PD and institutional support. PD programs that focus on TPACK development and foster collaborative learning can provide the necessary support for teachers to enhance their technological proficiency and integrate technology more effectively into their teaching practices (Vongkulluksn & So, 2021). Additionally, PD should focus not only on technology training but also on how to adapt pedagogy and content knowledge to make the best use of these tools.

The integration of technology into physics education offers numerous benefits, including increased student engagement, enhanced conceptual understanding, and improved problem-solving skills of the learners (Faresta et al., 2024). The TPACK framework provides a useful model for supporting teachers in integrating technology into their teaching practices. Mobile applications, in particular, offer significant potential for enhancing learning experiences in physics, providing interactive tools that help students visualize complex concepts (Pokhrel, 2024). Collaborative PD programs are key to fostering the skills and confidence needed for successful technology integration (Todorova & Osburg, 2010). However, ongoing support and training are essential to overcome the challenges teachers face when incorporating technology into their classrooms. As technology continues to evolve, it is crucial for PD programs to stay current and provide teachers with the resources they need to continuously improve their practice (Rosales, 2021).

METHODOLOGY

The TPACK framework illustrates the intersection of the three domains, underscoring the necessity for educators to blend technology, pedagogy, and content. This model aids teachers in evaluating their competencies and devising approaches to cultivate 21st century learning environments.

Based on the specificity of the research topic, a mixed methods research approach was selected as both a qualitative research and quantitative analysis method (Fetters & Freshwater, 2020). The data obtained through the quantitative research has already been published (Mgeladze et al., 2024). A recent study using the TPACK questionnaire analyzed data from Georgian physics teachers, identifying four key factors and providing recommendations for improving technology integration in physics teacher education. Successful implementation requires ongoing PD, adequate resources, and a supportive school culture.

The qualitative research utilizes a design-based research (DBR) method, which is often associated with design-based learning, or design-based science. DBR is an educational approach where researchers engage in the iterative process of designing, testing, and refining educational interventions (Barab & Squire, 2004). This method emphasizes the active role of researchers in shaping the design of the study, allowing them to draw from their expertise to select appropriate strategies and guide the research process (Wang & Hannafin, 2005). Design-based teaching strategies frequently incorporate technology use, aiming to address real-world challenges through the creation of innovative and meaningful solutions (Anderson & Shattuck, 2012). The goal of this specific design research is to study the impact of the physics teachers' training module (tailored for these courses), focusing on the integration of mobile applications into classroom instruction. The research instruments used in this study include interview and focus group interview methods, which served as the foundation for conducting the current research. Audio recordings of the interviews were made, followed by the transcription and analysis of the collected data.

Table 1. Demographic information of teachers participating in qualitative research

Characteristic	Details
Total sample size (N)	11 participants
Gender	Female (100%)
Age range	22-75 years
Rural schoolteacher	7
Urban schoolteacher	4

In October 2023, 11 physics teachers (including both private and public schools) were selected from various regions of Georgia (South Caucasian Republic) for participation in a training "integrating technologies into the physics classroom".

A series of six training/workshop sessions were conducted, with half of them held in-person at the SALiS Laboratory at Ilia State University and the remaining half conducted online via the Zoom platform due to various constraints. A focus groups were conducted with the teachers during the first training session and at the end of the training session. The questions for the focus group were based on the quantitative TPACK questionnaire (Graham et al., 2009), which enhances the validity of the data obtained through both quantitative and qualitative research methods.

During the training sessions, two mobile applications, "Phyphox"[1] and "Physics Toolbox Suite"[2], were introduced for integration into the teaching process. Both applications are free of charge and work on Android and iOS systems. In addition to these two apps, participant teachers also explored other apps and regularly shared their thoughts and experiences with each other, discussing these apps and integrating them into the teaching process.

The training sessions were held approximately once a month. Between sessions, teachers were assigned tasks that were reviewed and discussed in the subsequent training sessions, facilitating experience sharing.

In the qualitative research, the sample size was predetermined, with 11 teachers participating. In the description section of the research, participants were referred to by initials: N. K., N. F., M. T., I. T., M. Ts., N. Ch., N. Sh., T. G., M. K., M. Kh., and G. I.

Demographic information about the participants is provided in **Table 1**. Each interview had an intended duration of 60 (+/- 10) minutes.

The transcription coding was done using Nvivo 15 software. The qualitative research tool can be considered

[1] phyphox–Physical phone experiments
[2] Vieyra Software

Table 2. Categories

No	Categories	Teacher's quotations
1	Use of technology (general)	"*I frequently use a virtual laboratory in the classroom*" (M. T.). "*I use Colorado simulations as well as the CK-12 portal. I also frequently prepare presentations for my lessons and often utilize materials shared by my colleagues in the group, as there are many high-quality ready-made resources available*" (N. S.).
2	Use of mobile applications	"*Last year, my students participated in a project where they developed a mobile application. This year, I have received numerous applications from students eager to take part in similar projects*" (T. G.). "*Mobile applications have been incredibly helpful to me this month … I've become quite accustomed to using Phyphox, but it doesn't cover all topics. I wish there were an application that could be used for every lesson, serving as a comprehensive teaching manual*" (N. F.).
3	Trainings	"*I can confidently say that these trainings have been highly beneficial, and I aim to incorporate insights from each session into my teaching practice*" (M. T.). "*I am truly satisfied–with myself, the training experience, and the progress I've made. This journey allowed me to see things from a different perspective, critically evaluate my approach, and appreciate this valuable opportunity. I thoroughly enjoyed it and believe I made the most of it within the project framework*" (N. K.). "*We exchanged experiences, collaborated, explored new applications together, and discussed how to implement them effectively*" (G. I.).
4	Interest and motivation (regarding mobile devices and apps)	"*One key advantage is that students aren't just passively using their phones–they are actively involved in learning. We need to engage them in a way that integrates their devices into the lesson, so instead of being a distraction, their phones become tools for learning and participation*" (N. S.). "*Student involvement and motivation are steadily increasing. They are eager to see their results, which is fantastic. I really enjoyed the lesson, and the teacher successfully achieved the intended outcome. This experiment helped students grasp the theory much more effectively*" (M. K.).
5	Evaluation	"*In the absence of school laboratories, mobile applications and simulations–even the translated ones on colorado.ge–prove to be highly engaging and valuable*" (G. I.). "*This application holds great potential for the future. Given the strong student interest and its evident effectiveness, we plan to continue using it moving forward*" (M. K.).
6	Challenges (the Internet issues, power outages, school support, insufficient lesson hours, number of students, personal expenses, resource availability)	"*In smaller classes with 10-15 students, implementing technology is relatively easier and highly effective, especially for group work. However, … in larger classes, it becomes significantly more challenging*" (N. K.). "*I teach in a rural school with limited funding for the physics classroom. My only available tool is my phone–I don't have a projector or a laptop. The school owns a single functioning computer, but it is in the administration office, and I do not have access to it*" (I. T.). "*Having just two hours of physics per week is insufficient*" (M. T.).

reliable because each question was understood identically by the respondents, which is confirmed by their answers; two independent researchers worked on developing the codes; after the initial processing, the codes were reanalyzed to confirm their identical understanding, thus ensuring the reliability of the research results. Additionally, Cohen's kappa coefficient for reliability was calculated in Nvivo 15. The reliability was evaluated at the 80% agreement level.

RESULTS

Based on the analysis of the transcripts, categories and subcategories were identified through the consensus of two independent experts. After the analysis, coding, and optimization, the following categories emerged (**Table 2**):

1. **Use of technology (general)**–Regarding the use of technology, almost every teacher had a different and unique attitude. Their views turned out to be quite diverse, as is evident from their responses. All teachers reported that they use technology in class but the pace and intensity of use significantly varies. During the focus group, similar or different activities were often recalled based on each other's statements, so there was frequent deviation from the focus of the question and discussion of personal experiences. The diverse responses highlight both the potential and challenges of integrating technology into education. On the one hand, the variety of available tools and resources allows teachers to tailor their approaches to their unique teaching styles and the needs of their students. This personalization can lead to more engaging and effective learning experiences. Teachers report association between their use of technology for in-class experiments and the heightened interest among students.
2. **Use of mobile applications–**In this category, we discuss whether teachers had any prior

knowledge about using educational mobile applications, and if they used them. Out of the 11 selected teachers, several had previously used mobile applications; however, they are not satisfied with the variety of topics covered by these applications. The discussion on mobile applications revealed varying levels of prior knowledge and usage among teachers. Some teachers engaged with mobile applications through student projects, leading to increased interest and participation in such activities. Specific applications like Phyphox were highlighted as valuable tools for certain grade levels and topics, although there was a desire for more comprehensive applications that could be used consistently across different lesson plans. Overall, mobile applications are seen as beneficial, but there is a need for more versatile and widely applicable tools to support diverse educational needs.

3. **Training–**This category explores collaboration during the training and the practical application of knowledge acquired from sessions. It highlights the importance of teamwork among participants to share experiences and overcome challenges collectively. Additionally, it examines how the acquired knowledge can be tailored and implemented effectively in real-life educational settings to enhance teaching practices. These reflections underscore the importance of well-structured training sessions that provide practical, applicable knowledge and foster a collaborative learning environment. The positive feedback from teachers indicates the value they place on continuous PD and the integration of new strategies into their teaching practices.
4. **Interest and motivation (regarding mobile devices and apps)–**In this category, we will discuss how the use of mobile apps has influenced students' motivation and engagement in the learning process. The availability of interactive features in mobile apps has significantly enhanced students' curiosity and enthusiasm for learning. Moreover, the ability to access educational content anytime and anywhere has fostered a sense of independence and active participation in the learning journey. Overall, as teachers reported, mobile apps have enhanced student engagement, motivation, and participation in various educational activities.
5. **Evaluation–**In this category, we discuss the evaluation of how effectively mobile applications and technologies were used by the participant teachers, as well as their impact on improving their students' academic performance. Assessing the usability of mobile applications includes analyzing how well they cater to diverse learning needs and preferences. Additionally, evaluating the measurable outcomes, such as test scores and skill development, helps determine their effectiveness in boosting students' academic success.
6. **Challenges (the Internet issues, power outages, school support, insufficient lesson hours, number of students, personal expenses, resource availability)–**In this category, we explore the challenges faced when integrating technology. Teachers often struggle with inadequate technical support and training, which limits their ability to effectively integrate new tools into their teaching practices. Furthermore, the lack of affordable and easily accessible educational software and platforms presents a significant barrier to utilizing technology in classrooms. The identified challenges underscore the complexity of integrating technology into diverse educational settings. The disparity in class sizes highlights how resource limitations can exacerbate inequalities in educational quality and effectiveness. Language barriers, power outages, and internet access further complicate the effective use of technology.

DISCUSSION

The study reveals that the long-term training program significantly enhanced teachers' technological proficiency. Through structured training sessions that included hands-on activities, collaborative projects using technology, and continuous feedback, teachers became more confident and competent in using mobile applications to facilitate student learning. This aligns with previous research indicating that sustained PD is critical for effective technology integration in education (Darling-Hammond et al., 2017).

Collaborative Success

One of the notable outcomes of the training program was the development of a strong professional community among the teachers. The collaborative nature of the training fostered a culture of continuous improvement and mutual support. Teachers not only learned from the training sessions but also from each other, sharing experiences and best practices. This sense of community is essential for sustaining the gains made during PD and fostering ongoing innovation in teaching practices (Lieberman & Mace, 2010). Collaboration among teachers significantly improved their pedagogical practice. Sharing experiences helped in their professional growth, which was one of the main goals of the training sessions (Raveh et al., 2025)

Encouraging peer-to-peer learning and providing continuous PD opportunities may also enhance teachers' confidence and proficiency in using technology, ultimately leading to a more cohesive and enriched educational experience for students (Ertmer et al., 2012).

Impact on Teaching Practices and Effectiveness of Professional Development

The integration of mobile applications into physics lessons led to more engaging and effective learning experiences for students. Teachers reported that the use of mobile applications made lessons more interactive and helped students better understand complex physics concepts. This is consistent with the TPACK framework's emphasis on the intersection of technological, pedagogical, and content knowledge to enhance teaching effectiveness (Koehler & Mishra, 2005). The effectiveness of PD training for teachers significantly influences their ability to integrate new knowledge and skills into classroom practices (Desimone, 2009). The reflections shared by teachers highlight the impact of well-structured training sessions on their professional growth. Unlike short-term trainings that often fail to provide lasting benefits due to resource constraints, comprehensive and well-supported training programs can foster meaningful changes in teaching practices. Teachers' satisfaction with the recent training sessions underscores the importance of ongoing PD opportunities that are relevant, practical, and supported by adequate resources (Garet et al., 2001). The positive feedback indicates that teachers value the opportunity to critically evaluate their methods and incorporate new strategies into their teaching. This aligns with findings from prior research emphasizing the need for sustained, context-specific PD that enables teachers to apply new knowledge effectively (Loucks-Horsley et al., 2010).

Resource Availability and Infrastructure

The substantial gap in resource availability, particularly in underfunded rural schools, points to systemic issues that need addressing to ensure equitable access to educational technology. This includes investment in infrastructure and providing schools with necessary hardware such as projectors and computers (Kumari & Nigam, 2020). In schools without physical laboratories, mobile applications and simulations serve as a crucial alternative for hands-on learning experiences (Smith, 2022). These tools enable students to conduct experiments and explore scientific concepts in a virtual environment, which can be particularly beneficial in resource-limited settings. The reliance on virtual laboratories, while beneficial, indicates a pressing need for tangible laboratories to provide students with hands-on learning experiences that virtual simulations cannot fully replicate (Franklin & Bolick, 2007).

Enhancing Student Engagement with Mobile Applications

The evaluation of mobile applications and technologies in the classroom demonstrates their significant impact on enhancing student engagement and academic performance. Teachers reported that students who had previously been disengaged or underperforming showed increased activity and enthusiasm when interacting with mobile applications (Smith, 2022). This aligns with broader research indicating that technology can enhance student motivation and participation (D'Angelo, 2018). The use of mobile applications in the classroom exemplifies how technology can enhance learning experiences when effectively integrated into the curriculum (Ahmad Bhat, 2021). However, the challenges of resource limitations and access must be addressed to ensure all teachers can benefit from such tools. Providing continuous support and fostering a collaborative environment where educators can share best practices can help overcome these challenges (Kumari & Nigam, 2020). The use of mobile devices to create a collaborative classroom environment highlights the importance of leveraging technology to foster teamwork and efficient learning. By allowing students to complete tasks within the limited class time, mobile applications can enhance the overall effectiveness of classroom instruction (Smith, 2022).

Challenges and Recommendations

Despite the positive outcomes, the study also identified several challenges. Teachers faced issues related to resource availability, infrastructure, and support. To address these challenges, it is recommended that schools and educational authorities: Provide adequate resources and infrastructure to support technology integration. Offer ongoing support and PD opportunities to ensure that teachers can continue to develop their technological skills and adapt to new advancements in educational technology. Establish structured training and clear guidelines on how to effectively integrate technology. Create support systems and collaborative platforms where educators can share best practices and resources. Moreover, the personal expenses spent by teachers to compensate for inadequate school resources call for increased institutional support and funding. Encouraging the sharing of best practices and fostering a collaborative environment can help teachers navigate these challenges. Peer-to-peer learning and continuous PD opportunities may also enhance teachers' confidence and proficiency in integrating technology (Hew & Brush, 2007).

Limitations

Limitations refer to factors that may affect the validity, reliability, and generalizability of research findings. Recognizing these limitations is crucial for accurate interpretation of results.

1. **Data collection and measurement:** Methods may introduce biases or errors (e.g., self-reporting);
2. **Time constraints:** Short study durations might not adequately capture the long-term effects, and evolving circumstances over time could influence the findings' relevance.

CONCLUSION

The integration of TPACK and collaborative learning strategies has proven to be highly effective in enhancing technological proficiency in physics education. By leveraging these frameworks, educators are able to create a more engaging and interactive learning environment that fosters deeper understanding and retention of complex concepts (Mishra & Koehler, 2006). The collaborative learning approach not only encourages active participation and teamwork among students but also allows for the sharing of diverse perspectives, thereby enriching the learning experience (Johnson & Johnson, 2009). When combined with TPACK, which provides a comprehensive understanding of how technology can be effectively integrated into teaching practices, the result is a more dynamic and effective educational process (Koehler & Mishra, 2009).

This paper has demonstrated that the synergy between TPACK and collaborative learning can lead to significant improvements in both teaching and learning outcomes in physics education. As educators continue to adopt and refine these methods, the potential for technological proficiency and academic success in the field of physics will undoubtedly continue to grow (D'Angelo, 2018; Smith, 2022).

Despite the positive outcomes, challenges related to resource availability, infrastructure, and support were identified. To address these issues, it is crucial for schools and educational authorities to provide adequate resources, ongoing PD, and structured training. Strengthening partnerships with educational technology companies and community organizations can also provide essential resources and support.

Integrating TPACK and collaborative learning strategies into university programs is essential for preparing pre-service teachers to effectively utilize technology in their future classrooms. This approach equips future educators with the skills and knowledge needed to create engaging and interactive learning environments. By incorporating TPACK into teacher education programs, pre-service teachers can develop a comprehensive understanding of how to integrate technology into their teaching practices effectively. This preparation is crucial for fostering technological proficiency and improving student learning outcomes (Angeli & Valanides, 2009; Harris et al., 2009).

Collaborative learning strategies should also be emphasized in university programs, as they encourage active participation and teamwork among future educators. This approach helps pre-service teachers understand the value of diverse perspectives and how to create enriching learning experiences for their students (Gillies, 2016).

Addressing the financial strain on teachers and increasing institutional support will contribute to a more effective and sustainable integration of technology in education. By creating an environment where teachers feel supported and equipped, we can enhance the overall quality of education and better prepare students for the future. Ensuring equitable access to educational technology and fostering a collaborative environment will ultimately lead to a more cohesive and enriched educational experience for students.

Overall, we believe that this collaborative approach in physics teacher training, along with the integration of mobile applications into lessons, can be applied to other science subjects. It will significantly improve both teaching methods and learning outcomes in science education.

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AI statement: The authors stated that they used ChatGPT (OpenAI) exclusively for language editing and proofreading purposes. No content was generated by AI, and the authors take full responsibility for all intellectual content.

Declaration of interest: No conflict of interest is declared by the authors.

Data sharing statement: Data supporting the findings and conclusions are available upon request from the corresponding author.

REFERENCES

Ahmad Bhat, R. (2021). The impact of technology integration on student learning outcomes: A comparative study. *International Journal of Social Science Educational Economics Agriculture Research and Technology, 2*(9), 592-596. https://doi.org/10.54443/ijset.v2i9.218

Anderson, C. A., & Shattuck, J. (2012). Design-based research: An emerging paradigm for transforming learning in science. *Yearbook of the National Society for the Study of Education, 111*(2), 41-60.

Angeli, C., & Valanides, N. (2009). Epistemological and methodological issues for the conceptualization, development, and assessment of ICT-TPCK:

Advances in technological pedagogical content knowledge (TPCK). *Computers & Education, 52*(1), 154-168. https://doi.org/10.1016/j.compedu.2008.07.006

Angeli, C., & Valanides, N. (2019). The TPACK framework: A catalyst for the integration of technology in teacher education. *Education and Information Technologies, 24*(1), 39-55.

Barab, S. A., & Squire, K. D. (2004). Design-based research: An emerging paradigm for transforming science education. *Yearbook of the National Society for the Study of Education, 103*(1), 1-21.

Chai, C. S., Koh, J. H. L., & Tsai, C. C. (2016). A review of research on the TPACK framework in teacher education: A decade of development. *Educational Technology & Society, 19*(3), 1-11.

D'Angelo, C. (2018). *The impact of technology: Student engagement and success*. University of Ontario Institute of Technology.

Damayanti, A. E., & Kuswanto, H. (2021). The effect of the use of indigenous knowledge-based physics comics of android-based marbles games on verbal representation and critical thinking abilities in physics teaching. *Journal of Technology and Science Education, 11*(2), 581-593. https://doi.org/10.3926/jotse.1142

Darling-Hammond, L., Hyler, M. E., & Gardner, M. (2017). *Effective teacher professional development*. Learning Policy Institute. https://doi.org/10.54300/122.311

Desimone, L. M. (2009). Improving impact studies of teachers' professional development: Toward better conceptualizations and measures. *Educational Researcher, 38*(3), 181-199. https://doi.org/10.3102/0013189X08331140

Ertmer, P. A., Ottenbreit-Leftwich, A. T., Sadik, O., Sendurur, E., & Sendurur, P. (2012). Teacher beliefs and technology integration practices: A critical relationship. *Computers & Education, 59*(2), 423-435. https://doi.org/10.1016/j.compedu.2012.02.001

Faresta, R. A., Asrori, F. R., & Izzati, N. (2024). Utilization of technology in physics education: A literature review and implications for the future physics learning. *Lensa: Jurnal Kependidikan Fisika, 12*(2), 45-57. https://doi.org/10.33394/j-lkf.v12i1.11676

Fetters, M. D., & Freshwater, D. (2020). The mixed methods research guide. *International Journal of Multiple Research Approaches, 14*(2), 137-156. https://doi.org/10.29034/ijmra.v14n2a1

Franklin, C. A., & Bolick, C. M. (2007). *Technology integration: A review of the literature* [Paper presentation]. The Society for Information Technology & Teacher Education International Conference.

Fütterer, T., Omarchevska, Y., Rosenberg, J. M., & Fischer, C. (2019). How do teachers collaborate in informal professional learning activities? An epistemic network analysis. *Journal of Science Education and Technology, 33*(6), 796-810. https://doi.org/10.1007/s10956-024-10122-y

Garet, M. S., Porter, A. C., Desimone, L., Birman, B. F., & Yoon, K. S. (2001). What makes professional development effective? Results from a national sample of teachers. *American Educational Research Journal, 38*(4), 915-945. https://doi.org/10.3102/00028312038004915

Gillies, R. M. (2016). Cooperative learning: Review of research and practice. *Australian Journal of Teacher Education, 41*(3), 39-54. https://doi.org/10.14221/ajte.2016v41n3.3

Graham, C. R. (2009). TPACK development in science teaching: Measuring the TPACK confidence of in-service science teachers. *Educational Technology Research and Development, 57*(4), 235-250.

Harris, J., Mishra, P., & Koehler, M. (2009). Teachers' technological pedagogical content knowledge and learning activity types: Curriculum-based technology integration reframed. *Journal of Research on Technology in Education, 41*(4), 393-416. https://doi.org/10.1080/15391523.2009.10782536

Hew, K. F., & Brush, T. (2007). Integrating technology into K-12 teaching and learning: Current knowledge gaps and recommendations for future research. *Educational Technology Research and Development, 55*(3), 223-252. https://doi.org/10.1007/s11423-006-9022-5

Johnson, D. W., & Johnson, R. T. (2009). An educational psychology success story: Social interdependence theory and cooperative learning. *Educational Researcher, 38*(5), 365-379. https://doi.org/10.3102/0013189X09339057

Koehler, M. J., & Mishra, P. (2005). What happens when teachers design educational technology? The development of technological pedagogical content knowledge. *Journal of Educational Computing Research, 32*(2), 131-152. https://doi.org/10.2190/0ew7-01wb-bkhl-qdyv

Koehler, M. J., & Mishra, P. (2009). What is technological pedagogical content knowledge? *Contemporary Issues in Technology and Teacher Education, 9*(1), 60-70.

Koehler, M. J., & Mishra, P. (Eds.). (2016). *Handbook of technological pedagogical content knowledge (TPACK) for educators*. Routledge.

Kumari, A., & Nigam, S. (2020). Technology integration in education: A catalyst for transforming learning–The new education policy 2020 perspective. *International Journal of Creative Research Thoughts, 11*(9), 601-611.

Lee, H.-Y., Chung, C.-Y., & Wei, G. (2020). Research on technological pedagogical and content knowledge: A bibliometric analysis from 2011 to 2020. *Frontiers* *in Education, 7*. https://doi.org/10.3389/feduc.2022.765233

Lee, M. H., & Tsai, C. C. (2020). Developing a model of technology integration for teachers: An investigation into the effects of TPACK-based professional development. *Computers & Education, 149*, Article 103806. https://doi.org/10.1016/j.compedu.2019.103806

Lieberman, A., & Mace, D. H. P. (2010). Making practice public: Teacher learning in the 21st century. *Journal of Teacher Education, 61*(1-2), 77-88. https://doi.org/10.1177/0022487109347319

Limniou, M. (2021). The effect of digital device usage on student academic performance: A case study. *Education Sciences, 11*(3), Article 121. https://doi.org/10.3390/educsci11030121

Loucks-Horsley, S., Stiles, K. E., Mundry, S., Love, N., & Hewson, P. W. (2010). *Designing professional development for teachers of science and mathematics* (3rd ed.). Corwin Press. https://doi.org/10.4135/9781452219103

Mgeladze, A., Kapanadze, M., & Chakhaia, L. (2024). From measuring to action: The next steps in physics teachers' technological pedagogical content knowledge. *Science Education International, 35*(4), 429-438. https://doi.org/10.33828/sei.v35.i4.13

Mishra, P., & Koehler, M. J. (2006). Technological pedagogical content knowledge: A framework for teacher knowledge. *Teachers College Record, 108*(6), 1017-1054. https://doi.org/10.1111/j.1467-9620.2006.00684.x

Olimovna, M. G. (2023). The role of digital educational technologies in teaching physics. *Science and Innovation: International Scientific Journal, 2*(4). https://doi.org/10.5281/zenodo.7824362

Parker, C. E., Stylinski, C. D., Bonney, C. R., DeLisi, J., Wong, J., & Doty, C. (2019). Measuring quality technology integration in science classrooms. *Journal of Science Education and Technology, 28*(3), 567-578. https://doi.org/10.1007/s10956-019-09785-7

Pokhrel, S. (2024). Digital technologies in physics education: Exploring practices and challenges. *Teacher Education Advancement Network Journal, 15*(1), 37-48. https://doi.org/10.1007/s10956-020-09821-z

Raveh, I., Lavie, I., Wagner-Gershgoren, I., Miedijensky, S., Segal, R., & Klemer, A. (2025). Mathematics and science teachers: How their perceptions of their TPACK and use of technology interrelate. *Eurasia Journal of Mathematics, Science and Technology Education, 21*(1), Article em2565. https://doi.org/10.29333/ejmste/15803

Rosales, L. K. G. (2021). Technology integration: Implication for teachers' professional development. In *Proceedings of the Southeast Asian Conference on Education 2021* (pp. 55-68). https://doi.org/10.22492/issn.2435-5240.2021.5

Sánchez, A. R., & Barrientos, F. (2019). Exploring mobile learning in science education: A case study in physics. *Journal of Science Education and Technology, 28*(3), 274-283.

Shen, W., Lin, X.-F., Chiu, T. K. F., Chen, X., Xie, S., Chen, R., & Jiang, N. (2024). How school support and teacher perception affect teachers' technology integration: A multilevel mediation model analysis. *Education and Information Technologies, 29*, 25069-25091. https://doi.org/10.1007/s10639-024-12802-z

Smith, S. (2022). *Mobile technology: Opportunities and challenges in primary education*. Ontario Tech University.

Taşar, M. F., & Ergül, D. Y. (2023). Technological pedagogical content knowledge (TPACK) in physics education. In *Proceedings of the International Handbook of Physics Education Research: Teaching Physics* (pp. 1-30). AIP Publishing. https://doi.org/10.1063/9780735425712_001

Todorova, A., & Osburg, T. (2010). Professional development program for technology integration: Facilitators and barriers to sustainable implementation. *Literacy Information and Computer Education Journal, 1*(1), 93-102. https://doi.org/10.20533/licej.2040.2589.2010.0009

Vongkulluksn, V. W. L., & So, W. W. M. (2021). Collaborative learning in teacher professional development: A systematic review. *Teaching and Teacher Education, 98*, Article 103271. https://doi.org/10.1016/j.tate.2020.103271

Wang, F., & Hannafin, M. J. (2005). Design-based research and technology-enhanced learning environments. *Educational Researcher, 34*(6), 6-18.

Zhai, X., Li, L., & Chen, Y. (2020). Promoting problem-solving skills through mobile technologies in physics education. *Education Sciences, 10*(2), 123-135. https://doi.org/10.3390/educsci10020043

Zhai, X., Liu, M., & Li, Y. (2022). Effects of mobile learning on students' academic achievement: A meta-analysis of experimental studies. *Computers & Education, 177*, Article 104375.