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Research Insights
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KEY DRIVERS OF PRIMARY PRE-SERVICE TEACHERS' TPACK DEVELOPMENT AND TECHNOLOGY ADOPTION IN STEM EDUCATION: INSIGHTS FROM COLLABORATIVE E-LEARNING

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Abstract. This study examines key factors influencing primary pre-service teachers' development of Technological Pedagogical Content Knowledge (TPACK) in STEM education through e-learning and their adoption of technology in future practice. Conducted in Serbia with 186 primary pre-service teachers engaged in online collaborative learning, the study employs multiple linear regression to analyze the effects of subjective norm, perceived usefulness and ease of use of technology, teacher quality in e-learning, perceived usefulness of collaborative learning, facilitating conditions in e-learning, technological knowledge, content knowledge, and TPACK. Results indicate that primary pre-service teachers' TPACK is primarily shaped by content knowledge, the perceived usefulness of collaborative learning, and ease of technology use. Their intention to use technology in STEM teaching is influenced by TPACK, content knowledge, and teacher quality. These findings suggest that teacher education programs should prioritize strengthening content knowledge, enhancing the quality and perceived value of collaborative e-learning, and developing teachers' digital competence to support effective TPACK growth and meaningful technology integration in STEM education.

Keywords: TPACK; STEM education; e-learning; collaborative learning; technology adoption; pre-service teachers

Introduction

The Technological Pedagogical Content Knowledge (TPACK) framework represents a comprehensive model that defines the types of knowledge educators need to effectively integrate technology into teaching (Thompson & Mishra, 2007). It consists of three core domains: Technological Knowledge (TK): the ability to understand and use various technologies; Pedagogical Knowledge (PK): the ability to apply diverse teaching strategies; and Content Knowledge (CK): a deep understanding of the subject matter.

TPACK highlights that proficient use of technology in the classroom necessitates more than simply technical know-how; it also entails the capacity to integrate technology with subject matter and pedagogical approaches. Educators must develop integrated knowledge that enables them to use technology to enhance student learning (Schmidt et al., 2009).

Recent research has shown that well-designed teacher education programs can significantly strengthen educators' TPACK, particularly when they include hands-on, practice-based experiences within authentic teaching contexts (Ning et al., 2022). Studies involving emerging technologies, such as the Metaverse, confirm TPACK's continued relevance in diverse digital contexts (Al-Maroof et al., 2024).

In addition, the TPACK framework has increasingly been recognized as dynamic and context-sensitive. Recent findings indicate that its application varies depending on instructional settings and the experience level of educators. Tschönhens et al. (2024) demonstrated that both pre-service and in-service teachers adapt their use of technological, pedagogical, and content knowledge according to specific classroom contexts. These findings underscore the need for flexible, adaptive teacher training programs.

STEM education presents unique challenges and opportunities for technology integration, particularly due to its focus on interdisciplinary learning and real-world problem solving (Honey & Pearson, 2014). The TPACK framework becomes especially relevant in this context, as teaching STEM subjects often requires the use of advanced digital tools and inquiry-based strategies (Niess, 2012). Integrating TPACK into STEM education can enhance instructional quality and support the development of students' critical thinking skills (Sheffield et al., 2015).

Collaborative online group work plays a pivotal role in fostering the development of Technological Pedagogical Content Knowledge (TPACK), particularly within STEM education, where teamwork, problem-solving, and interdisciplinary thinking are essential (Wahono et al., 2025). Engaging in collaborative digital tasks enables pre-service teachers to experiment with technological tools, co-construct pedagogical strategies, and integrate subject-specific content meaningfully. Recent studies have shown that such environments encourage reflection, peer learning, and authentic practice – factors that are critical to building the interconnected knowledge domains of TPACK (McDougall & Phillips, 2024; Wahono et al., 2025).

Despite the increasing body of literature on TPACK (Ma et al. 2024; Tembrevilla et al., 2024), few studies have examined how TPACK develops specifically in collaborative e-learning environments, particularly among pre-service teachers preparing for STEM education. Existing studies primarily focus on in-service teachers or general technology use, without addressing TPACK development in collaborative settings. Furthermore, while intention to adopt technology is frequently explored in general terms, its specific relationship with TPACK and contextual variables in STEM settings remains under-investigated.

Accordingly, this study addresses these gaps by investigating how pre-service teachers develop TPACK within collaborative e-learning environments and identifying key factors that influence their intention to integrate technology into future STEM teaching. The findings aim to inform teacher education programs and enhance digital teaching competencies in STEM.

Literature review

Integrating technology has become a key priority in contemporary education, particularly in STEM (science, technology, engineering, and mathematics) classrooms. Advances in digital tools and platforms present new opportunities to enhance both instructional practices and student learning outcomes.

The Technology Acceptance Model (TAM) explains technology use based on perceived usefulness (PU) and ease of use (PEU), both influencing behavioral intention (Davis, 1989). PEU refers to "the extent to which a person believes that using a particular system will require minimal effort," while PU is defined as "the extent to which a person believes that using a particular system will improve their performance" (Davis, 1989, p. 320). Complementing TAM, Fishbein and Ajzen's (1975) Theory of Reasoned Action (TRA) highlights the influence of subjective norms on individuals' behavioral intentions. TRA posits that individuals act in line with perceived expectations of significant others. Recent studies revealed that social influence, i.e. subjective norm was the most significant factor affecting university students' attitudes and behavioral intentions to use the Internet-based technology for learning (Huang et al. 2020). These findings suggest that fostering a supportive social environment and ensuring enjoyable learning experiences are crucial for encouraging students to use technology.

The E-learning Acceptance Model (ElAM) introduces other relevant constructs such as teacher quality in e-learning (EL_TQ) and facilitating conditions (EL_FC). These factors reflect the perceived support and guidance students receive from instructors and the infrastructure that enables effective online collaboration (Tarhini et al. 2016). Perceived usefulness of online collaboration (EL_PU), combined with teacher support and digital competence, significantly shapes students' attitudes toward technology use (Ertmer & Ottenbreit-Leftwich, 2010). The study by Elgort et. al. (2008) shows that wiki platforms can effectively support group tasks by encouraging active engagement, learner autonomy, and the development of collaborative skills. However, the successful use of such tools also depends on instructional design and the teacher's role in facilitating the process, further emphasizing the importance of teachers in the context of educational technology integration.

The Technological Pedagogical Content Knowledge (TPACK) framework, building on Shulman's concept of pedagogical content knowledge, integrates technological knowledge into effective teaching practices (Harris et al. 2009; Schmidt et al. 2009). TPACK emphasizes the complex interaction among content, pedagogy, and technology knowledge, which is essential for successful technology integration in education (Voogt et al., 2013). TK includes digital and non-digital tools, while CK refers to subject-specific understanding (Mishra & Koehler, 2006). Teachers must understand the subject matter they will teach and the ways in which knowledge varies among subject areas. Recent studies highlight that digital pedagogy based on cooperation improves both TPACK and academic performance (Meroño et al., 2021), and that collaborative technologies enhance TPACK and reflective practice (Tembrevilla et al., 2024).

Together, TAM, TRA, ElAM, and TPACK provide a robust conceptual framework for analyzing pre-service teachers' adoption of technology in STEM contexts.

Method

Aim of the study

Based on the literature review in the field of TPACK, technology acceptance in STEM education and collaborative e-learning, this research aims to examine the variables that influence TPACK and the acceptance of technology to enhance pedagogical innovations in STEM education. The variables studied include: the intention to use technology in STEM education (BISTEM), subjective norm (SN), perceived usefulness of technology (PU), perceived ease of use of technology (PEU), teacher quality in e-learning (EL_TQ), perceived usefulness of online group work (EL_PU), facilitating conditions in e-learning (EL_FC), technological knowledge (TK), content knowledge (CK), and technological pedagogical content knowledge (TPACK).

This study seeks to answer the following research questions:

1. To what extent do the variables SN, PU, PEU, EL_TQ, EL_PU, EL_FC, TK, and CK predict TPACK in pre-service teachers?
2. To what extent do the variables SN, PU, PEU, EL_TQ, EL_PU, EL_FC, TK, CK, and TPACK predict the intention of pre-service teachers to use digital technologies in STEM education (BISTEM)?

Research sample

The sample included 186 third-year undergraduate pre-service primary school teachers from the Faculty of Education in Jagodina, Serbia. These students are preparing to become generalist primary school teachers (grades 1^{st} – 4^{th}), which means they are expected to teach all core subjects, including mathematics, digital literacy, and science.

During a mandatory course (Methodology of Computer Science Education), students worked for eight-weeks in small groups (3 – 5 members) using PBworks – a collaborative wiki platform – to design instructional materials for primary mathematics and science. The instructor provided guidance and formative feedback within the platform.

Survey data were collected after the completion of the eight-week collaborative project. The instrument used for data collection is provided in the Appendix. Ethical principles were strictly adhered to, and participants voluntarily took part in the study. The questionnaire was paper-based and completed anonymously. Out of the total number, 25 (13.4%) students were male. The average age of the participants was 21.86 (SD 1.072) years. On average, it took approximately 10 minutes to complete the questionnaire.

Instrument and data analysis

The research instrument was a structured questionnaire composed of validated scales adapted from the E-learning Acceptance Measure (Teo 2010), TAM (Davis 1989), TRA (Fishbein & Ajzen 1975; Venkatesh et al. 2003), and the Technological Pedagogical Content Knowledge (TPACK) framework (Schmidt et al. 2009), tailored to the Serbian educational context and the scope of this study. The initial section gathered data on participants' demographic profiles, such as their age and gender. The instrument included 53 items across ten validated constructs, each rated on a five-point Likert scale.

Descriptive statistics and multiple linear regression were conducted in SPSS 23. Exploratory factor analysis (EFA) confirmed construct validity, and all scales demonstrated good internal consistency ($\alpha > 0.70$). Assumptions for multiple regression were met, including normality, absence of multicollinearity, and no significant outliers. Multiple linear regression was then conducted to examine the predictive relationships between variables. All analyses were performed using SPSS.

Results

Descriptive statistics

Descriptive statistics were conducted to assess the central tendency, variability, and distribution of the study variables, as shown in Table 1. The mean values indicated general agreement with the statements on the five-point Likert scale, with most variables showing moderate to high mean scores, suggesting positive perceptions among participants. Standard deviations were moderate, indicating a reasonable spread of responses around the mean.

Table 1. Descriptive statistics results

Variable	Mean	Standard Deviation	Skewness	Kurtosis	Cronbach's Alph (a)
SN	3.5143	1.03070	-0.344	-0.348	0.86
PU	4.3637	0.76403	-1.033	0.151	0.90
PEU	4.3137	0.75455	-1.236	1.591	0.89
EL_TQ	4.3999	0.71857	-1.083	0.073	0.94
EL_PU	4.2748	0.68503	-0.589	-0.610	0.94

EL_FC	4.3544	0.75483	-0.988	0.042	0.84
TK	3.6306	0.84139	-0.231	0.099	0.90
CK	4.0252	0.87160	-0.753	0.266	0.91
TPACK	4.0169	0.71196	-0.274	-0.508	0.95
BISTEM	4.2696	0.64828	-0.516	-0.577	0.93

Note: SN – Subjective Norm; PU – Perceived Usefulness of Technology; PEU – Perceived Ease of Use of Technology; EL_TQ – Teacher Quality in E-Learning; EL_PU – Usefulness of Online Group Work; EL_FC – Facilitating Conditions in E-Learning; TK – Technological Knowledge; CK – Content Knowledge; TPACK – Technological Pedagogical Content Knowledge; BISTEM – Intention to Use Technology in STEM Education

The skewness and kurtosis values further suggest that the data distributions are approximately normal, with skewness values ranging from -1.236 to -0.231 and kurtosis values between -0.610 and 1.591, all within acceptable thresholds for normality (Kline, 2010). Additionally, Cronbach's Alpha values, which measure the internal consistency of each scale, ranged from 0.84 to 0.95, all exceeding the recommended threshold of 0.70 (DeVellis, 2003). These results confirm the reliability of the scales used in this study.

Table 2. Exploratory factor analysis (EFA) results

	Components									
	TPACK	**EL_TK**	**SN**	**TQ**	**BISTEM**	**EL_PU**	**PU**	**CK**	**PEU**	**EL_FC**
EL_PU1						.507				
EL_PU2						.631				
EL_PU3						.800				
EL_PU4						.846				
EL_PU5						.870				
EL_PU6						.880				
EL_FC1										.606
EL_FC2										.842
EL_FC3										.903
EL_TQ1		.886								
EL_TQ2		.830								
EL_TQ3		.769								
EL_TQ4		.797								
EL_TQ5		.725								
EL_TQ6		.783								
EL_TQ7		.706								

EL_TQ8		.409						
TK1				.616				
TK2				.693				
TK3				.800				
TK4				.843				
TK5				.871				
TK6				.741				
CK1							-.820	
CK2							-.827	
CK3							-.826	
TPACK1	.588							
TPACK2	.595							
TPACK3	.670							
TPACK4	.679							
TPACK5	.687							
TPACK6	.742							
TPACK7	.812							
TPACK8	.898							
TPACK9	.739							
TPACK10	.606							
PU1						-.723		
PU2						-.835		
PU3						-.824		
PU4						-.624		
PEU1						-.313		-.656
PEU2								-.714
PEU3								-.798
PEU4								-.679
SN1			.879					
SN2			.878					
SN3			.784					
BISTEM1					.613			
BISTEM2					.769			
BISTEM3					.764			
BISTEM4					.813			
BISTEM5					.816			
BISTEM6					.808			

Note: Extraction Method: Principal Component Analysis; Rotation Method: Oblimin with Kaiser Normalization

An exploratory factor analysis (EFA) was conducted using Principal Component Analysis (PCA) with Oblimin rotation and Kaiser normalization. The results, presented in Table 2, indicated that the items loaded strongly onto their respective factors, demonstrating a clear factor structure. The eigenvalues for all factors exceeded 1, further confirming the adequacy of the factor model. These results support the reliability and validity of the scales used to assess key drivers of technology adoption in STEM education.

Table 3. Correlation

	SN	PU	PEU	EL_TQ	EL_PU	EL_FC	TK	CK	TPACK
PU	.448**								
PEU	.270**	.553**							
EL_TQ	.237**	.505**	.572**						
EL_PU	.142	.408**	.470**	.624**					
EL_FC	.051	.297**	.405**	.599**	.538**				
TK	.004	.193**	.331**	.192**	.381**	.200**			
CK	.059	.169*	.295**	.223**	.415**	.283**	.543**		
TPACK	.133	.287**	.437**	.354**	.600**	.355**	.467**	.552**	
BISTEM	.112	.320**	.402**	.427**	.561**	.326**	.378**	.518**	.690**

**$p<0.01$; *$p<0.05$

Note: SN – Subjective Norm; PU – Perceived Usefulness of Technology; PEU – Perceived Ease of Use of Technology; EL_TQ – Teacher Quality in E-Learning; EL_PU – Usefulness of Online Group Work; EL_FC – Facilitating Conditions in E-Learning; TK – Technological Knowledge; CK – Content Knowledge; TPACK – Technological Pedagogical Content Knowledge; BISTEM – Intention to Use Technology in STEM Education.

Based on Table 3, TPACK is most strongly correlated with Perceived Usefulness of Online Group Work (EL_PU), Technological Knowledge (TK), Content Knowledge (CK), and Perceived Ease of Use (PEU). On the other hand, Behavioral Intention to Use Technology in STEM Education (BISTEM) shows the strongest correlation with TPACK, followed by EL_PU, CK, and Teacher Quality in E-Learning (EL_TQ).

Table 4. Multiple regression results for dependent variable TPACK

Model 1	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	*Beta*	*t*	*Sig.*
(Constant)	.521	.309		1.686	.094
SN	.030	.041	.044	.735	.464
PU	-.019	.066	-.020	-.284	.777
PEU	.157	.068	.166	2.298	.023
EL_TQ	-.097	.082	-.098	-1.191	.235
EL_PU	.423	.079	.407	5.333	.000
EL_FC	.026	.066	.027	.395	.694
TK	.101	.056	.119	1.811	.072
CK	.232	.054	.284	4.308	.000

Table 4 presents the results of a multiple regression analysis for the dependent variable TPACK. The predictors explained 48.2% of the variance in the TPACK variable ($R^2 = 0.482$, $F (8,177) = 5.912$, $p < 0.01$). It was determined that EL_PU predicts TPACK ($\beta = 0.407$, $p < 0.01$), as well as CK ($\beta = 0.284$, $p < 0.01$) and PEU ($\beta = 0.166$, $p < 0.05$). Other variables, such as SN, PU, EL_TQ, and EL_FC, were not significant predictors of TPACK in this model. TK approached significance with a positive relationship but was not statistically significant ($p = 0.072$). These findings suggest that EL_PU and CK are particularly important in shaping TPACK, while the impact of other factors is less pronounced in this model.

Table 5. Multiple regression results for dependent variable BISTEM

Model 2	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	*Beta*	*t*	*Sig.*
(Constant)	1.006	.271		3.713	.000
SN	-.028	.036	-.045	-.780	.437
PU	.053	.058	.063	.923	.357
PEU	.000	.060	.000	-.007	.994
EL_TQ	.153	.071	.169	2.147	.033
EL_PU	.113	.074	.120	1.529	.128
EL_FC	-.065	.057	-.076	-1.146	.253
TK	-.020	.049	-.025	-.399	.691
CK	.144	.049	.194	2.922	.004
TPACK	.436	.065	.479	6.670	.000

Note: SN – Subjective Norm; PU – Perceived Usefulness of Technology; PEU – Perceived Ease of Use of Technology; EL_TK – Teacher Quality in E-Learning; EL_PU – Usefulness of Online Group Work; EL_FC – Facilitating Conditions in E-Learning; TK – Technological Knowledge; CK – Content Knowledge; TPACK – Technological Pedagogical Content Knowledge; BISTEM – Intention to Use Technology in STEM Education.

Table 5 presents the results of a multiple regression analysis for the dependent variable BISTEM, which represents the intention to use technology in STEM education. The results showed that the predictors explained 52.8% of the variance in the BISTEM variable ($R^2 = 0.528$, $F (9, 176) = 4.759$, $p < 0.01$). It was determined that TPACK ($\beta = 0.479$, $p < 0.01$) directly predicts BISTEM, as well as CK ($\beta = 0.194$, $p < 0.01$) and EL_TQ ($\beta = 0.169$, $p < 0.05$). On the other hand, SN, PU, PEU, EL_PU, EL_FC, and TK were not significant predictors of BISTEM in this model. The results suggest that TPACK and CK play a crucial role in shaping future teachers‘ intention to use technology in STEM education.

Discussion

This study aimed to examine the key factors influencing two critical dimensions of technology integration among pre-service teachers: the development of their Technological Pedagogical Content Knowledge (TPACK) and their behavioral intention to use technology in future STEM instruction (BISTEM).

Results indicate that the development of TPACK is most significantly influenced by three constructs: the perceived usefulness of online collaborative learning (EL_PU), content knowledge (CK), and the perceived ease of use of technology (PEU). These findings are consistent with those of Sun et al. (2024), who demonstrated a strong correlation between perceived usefulness and TPACK in the context of technology acceptance among pre-service STEM teachers. Moreover, the significant influence of PEU on TPACK supports the core tenets of the Technology Acceptance Model (TAM), which postulates that perceptions of ease of use directly impact positive attitudes and willingness to adopt technology (Davis, 1989). The positive impact of EL_PU suggests that meaningful collaboration in digital environments where prospective teachers engage in authentic tasks, interact with peers, and participate in collective problem-solving can foster deeper pedagogical reflection and more flexible integration of technology. This aligns with prior research emphasizing the role of collaboration in TPACK development (McDougall & Phillips, 2024).

Content knowledge emerged as another critical determinant of TPACK. The role of content knowledge in TPACK development further corroborates previous findings emphasizing the importance of disciplinary knowledge for effective technology integration (Voogt et al., 2013). Without a solid understanding of the content they teach, educators struggle to integrate technology in ways that genuinely enhance learning. Even though technological knowledge (TK) was not a statistically significant predictor in the regression model, it showed a moderate correlation with TPACK, suggesting that it may contribute indirectly or in interaction with other factors. This finding aligns with studies emphasizing that TK alone is insufficient unless contextualized within pedagogical and content-specific strategies (Wachira & Keengwe, 2011).

Although subjective norms, general perceived usefulness of technology, teacher quality in e-learning, facilitating conditions, and technological knowledge were also included in the model, they did not emerge as significant direct predictors of TPACK. However, prior research suggests these variables may exert indirect effects through mediating relationships within technology acceptance models. For example, Venkatesh and Davis (2000) demonstrated that subjective norms may influence perceived usefulness, indicating a more complex network of relationships between individual characteristics and technology adoption behaviors.

Regarding the intention to use technology in STEM education (BISTEM), TPACK emerged as the most significant predictor. This finding corroborates previous studies that emphasize integrated knowledge of technology, pedagogy, and content as the key to empowering teachers in digital environments (Sun et al., 2024). This is further supported by Joo et al. (2018), who found that TPACK significantly influenced science teachers' behavioral intention to integrate technology, particularly when supported by e-learning environments and technological self-efficacy. Similar findings were reported in a study conducted in the context of higher education in India, where Jain and Raghuram (2024) identified TPACK as a dominant predictor of both faculty and student willingness to adopt generative AI tools for educational purposes. Additionally, Sun et al. (2024) reported that STEM pre-service teachers' TPACK strongly influence their intention to use technology in the classroom, even more than PU, PEU or self-efficacy, emphasizing the need for targeted professional development in STEM education.

In addition to TPACK, content knowledge (CK) and e-learning teacher quality (EL_TQ) were significant predictors of BISTEM in our study. These findings are consistent with previous research highlighting the foundational role of CK in enabling effective technology integration. Anthony et al. (2021) emphasized that instructors' content knowledge and pedagogical readiness are key factors influencing their willingness to adopt blended learning strategies in higher education.

The higher evaluations of EL_TQ and a more favorable attitude toward the integration of e-learning tools in future STEM teaching can also be attributed to the structured use of the PBworks platform, accompanied by clear instructions and continuous instructor support. This authentic, collaborative digital environment likely enhanced perceptions of relevance and pedagogical value, consistent with some other studies. Al-Fraihat et al. (2020) and Mohammadi (2015) demonstrated that perceived e-learning quality including teaching effectiveness, course design, and learner support substantially affects instructors' and learners' acceptance of digital learning platforms.

Overall, TPACK, content knowledge and high-quality digital environments are essential for fostering meaningful technology adoption among future STEM educators.

Implications for Educational Policy and Practice

The findings of this study underscore the importance of embedding collaborative digital learning experiences within teacher preparation programs. When pre-service teachers engage in meaningful online interactions, they are more likely to develop interconnected TPACK structures. In the context of STEM education, where problem-solving and real-world application are essential to effective teaching and learning, such collaboration not only enhances the educational process but also assists aspiring educators in utilizing technology in genuine, meaningful ways. This highlights the value of creating e-learning environments that encourage active participation and pedagogical reflection in STEM teaching.

A strong emphasis on content knowledge (CK) is equally important, as it forms the foundation for selecting appropriate technologies and designing effective, content-aligned instruction. Programs should link content knowledge with opportunities to apply digital tools. Strengthening the connection between content expertise and digital pedagogy can empower teachers to make informed instructional choices and improve student learning outcomes.

Moreover, the perceived ease of use of technology emerged as a key factor in shaping TPACK. This suggests that teacher training should include guided, hands-on experiences with intuitive digital.

The study also emphasizes the need to improve the quality of teaching in digital contexts. The effectiveness of e-learning instructors – through effective digital pedagogy – can significantly influence pre-service teachers' motivation to adopt technology in their future classrooms. Teacher education institutions should invest in the professional development of faculty to model best practices in online instruction.

Finally, while some contextual factors such as subjective norms and facilitating conditions did not directly predict TPACK in this study, previous research suggests they may operate indirectly. Creating a supportive institutional culture that values digital innovation, supported by leadership and infrastructure, is essential to fostering sustained technology integration.

To foster meaningful technology integration in education, it is essential to establish ongoing professional development opportunities that equip teachers with both pedagogical and technical skills. Workshops, coaching sessions, and peer-learning initiatives should be designed to enhance educators' capacity to implement new digital tools with pedagogical intent. Educational policies should provide financial and structural incentives for technology adoption and support programs. Policies should include mechanisms for evaluating implementation. Feedback from teachers and students can support data-driven improvement in technology use.

Limitation of The Study and Future Research

This study was conducted with primary pre-service teachers from a single institution in Serbia, limiting the generalizability of findings. Variations in technological infrastructure, curricular frameworks, and cultural norms may significantly affect the applicability of the results to other settings.

Data were collected cross-sectionally, limiting causal inference and insights into TPACK development over time. Longitudinal research is needed to track changes as teachers enter the profession. Reliance on self-reported data may introduce response bias. Future studies should incorporate observational or performance-based measures.

Contextual factors like access to technology, support, and prior exposure were not addressed but may influence TPACK and adoption Further research should examine these elements to better understand enabling conditions.

Future work should examine how pedagogies fostering student agency and collaboration interact with teacher-level factors like TPACK. These insights can inform teacher education focused on student-centered, technology-enhanced learning.

Conclusion

This study emphasizes the critical role of several key factors in facilitating the integration of technology into STEM education, particularly within the context of teacher preparation and professional development. The results indicate that the development of TPACK is significantly shaped by the perceived usefulness of online collaborative learning, content knowledge, and perceived ease of use. Since TPACK emerged as the strongest predictor of future teachers' intention to use technology in STEM instruction, these factors indirectly support technology integration by enhancing TPACK. In addition to the central role of TPACK, the findings reveal that content knowledge and e-learning teacher quality also significantly predict pre-service teachers' behavioral intention to integrate technology into STEM education. This highlights the importance of not only disciplinary expertise but also the quality of instructional support and design in digital learning environments.

These results highlight the transformative potential of online collaborative environments as powerful catalysts for the development of TPACK competencies. Engaging in structured digital group activities allows prospective teachers to navigate the complex interplay among technology, pedagogy, and content. Through authentic learning tasks, collaborative problem-solving, and reflective dialogue, future educators enhance their pedagogical adaptability and preparedness for diverse and technologically mediated classroom contexts.

Furthermore, the study underscores the necessity of continuous professional development and targeted support aimed at strengthening technological literacy. High-quality interaction in e-learning environments, especially when facilitated by knowledgeable and supportive instructors combined with solid subject matter expertise, significantly enhances pre-service teachers' confidence and capacity to effectively apply digital tools. This aligns with broader educational imperatives that prioritize digital competence as a core element of modern teaching.

In conclusion, fostering the development of TPACK through content-rich, collaborative, and reflective digital practices provides a robust foundation for preparing future educators. By cultivating these integrated competencies, teacher education programs can more effectively equip pre-service teachers to design and implement pedagogical approaches that respond to the evolving demands of STEM education in digitally enriched learning environments.

APPENDIX

LIST OF SCALES AND CORRESPONDING ITEMS USED IN THIS STUDY

ELAM – E-learning Acceptance Measure (adapted from Teo (2010)

EL_TQ – Teacher quality in e-learning

During online group work in the wiki:

EL_TQ1 My teacher was able to explain concepts clearly.

EL_TQ2 My teacher was knowledgeable about ICT technology.

EL_TQ3 I was satisfied with the responses I received from my teacher.

EL_TQ4 My teacher was focused on helping me learn.

EL_TQ5 The learning activities were well-organized.

EL_TQ6 My teacher was available when I needed to consult with them.

EL_TQ7 My teacher was patient in communicating with me.

EL_TQ8 Group work was well-supported.

EL_PU – Perceived Usefulness of online group work

As a result of online group work in the wiki:

EL_PU1 I can make a more significant contribution to my future job.

EL_PU2 I can creatively incorporate ICT technology into my future job.

EL_PU3 I know how to find, evaluate, and select appropriate IT resources to support my work.

EL_PU4 I am able to accept and adapt ICT resources to my work.

EL_PU5 I can integrate ICT into my future work with minimal assistance.

EL_PU6 I can use ICT resources more efficiently in my future workplace.

EL_FC – Facilitating conditions in e-learning

When I needed help using the online environment:

EL_FC1 Specialized instructions were available to assist me.

EL_FC2 A specific person was available to provide support.

EL_FC3 I knew where to find the support.

TPACK – Technological Pedagogical Content Knowledge (adapted from Schmidt et al. (2009)).

TK – Technological Knowledge

TK1 I know how to solve my own technical problems.

TK2 I can easily learn ICT technology.

TK3 I follow all important new ICT technologies.

TK4 I often enjoy experimenting with various possibilities of new ICT technology.

TK5 I am familiar with many different ICT technologies.

TK6 I have the technical skills needed to use ICT technology.

CK – Content Knowledge

CK1 I have sufficient knowledge in STEM subjects.

CK2 I know how to think in terms of STEM subjects.

CK3 I have various methods and strategies that help me better understand STEM subjects.

TPACK – Technological Pedagogical Content Knowledge

TPACK1 I know about technologies I can use to understand and work with STEM subjects in teaching.

TPACK2 I can choose technologies that enhance teaching approaches in STEM classrooms.

TPACK3 I can choose technologies that enhance student work in STEM classrooms.

TPACK4 I think critically about how to use ICT technology in my STEM teaching.

TPACK5 I can adapt the use of ICT technologies I learn about to suit different teaching activities.

TPACK6 I can deliver lessons that appropriately combine the content of STEM subjects, ICT technology, and teaching approaches.

TPACK7 I can choose ICT technologies for my STEM teaching that enhance what I teach, how I teach, and what students learn.

TPACK8 I can use strategies that combine STEM subject content, ICT technologies, and teaching approaches I have learned in my STEM teaching.

TPACK9 I can provide guidelines for others to coordinate the use of STEM subject content, ICT technology, and teaching approaches in their school and/or college.

TPACK10 I can choose ICT technologies that enhance the content of STEM subject teaching.

SN – Subjective Norm (adapted from Fishbein & Ajzen (1975), and Venkatesh et al. (2003)

SN1 People whose opinions I respect encourage me to use ICT technology.

SN2 People who are important to me will support me in using ICT technology.

SN3 People who have an influence on my behavior think I should use ICT technology.

PU – Perceived Usefulness of technology (adapted from Davis (1989), and Teo (2009))

PU1 Using ICT technology will improve my work.

PU2 Using ICT technology will increase my efficiency.

PU3 Using ICT technology will increase my productivity.

PU4 I consider ICT technology a useful tool in my work.

PEU – Perceived Ease of Use of technology (adapted from Davis (1989), and Teo (2009))

PEU1 What I do with ICT technology is clear and understandable to me.

PEU2 It is easy for me to get ICT technology to do what I want.

PEU3 I find it easy to use ICT technology.

PEU4 It would be easy for me to become proficient in using ICT technology.

BISTEM – Behavioral Intention to Use Technology in STEM education (adapted from Davis (1989), and Teo (2009))

BISTEM1 I plan to use ICT technology frequently in teaching STEM subjects.

BISTEM2 I will probably use ICT technology in teaching STEM subjects as soon as I start working.

BISTEM3 I will use ICT technology in teaching STEM subjects in the future.

BISTEM4 I plan to use ICT technology frequently in teaching.

BISTEM5 I will probably use ICT technology in teaching as soon as I start working.

BISTEM6 I will use ICT technology in teaching in the future.

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