MODESTUM EURASIA Journal of Mathematics, Science and Technology Education, 2026, 22(2), em2774
ISSN:1305-8223 (online)
OPEN ACCESS Review Article https://doi.org/10.29333/ejmste/17826

Pre-service physics teachers' efficacy in using digital technologies for teaching optics

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Received 12 October 2025 ▪ Accepted 12 January 2026

Abstract

The main purpose of this study is to examine pre-service physics teachers' competencies in integrating digital technologies into the teaching of optics topics. In the study in which the quantitative research method was adopted, data were collected from 356 physics teacher candidates through ICT-TPACK-science scale, optical teaching self-efficacy scale and digital technology use scale in physics. Descriptive statistics, independent groups t-test, one-way ANOVA, Pearson correlation analysis and multiple linear regression analysis were used in the analysis of the data. The research findings showed that the technological pedagogical content knowledge (TPACK) levels of the physics teacher candidates were high, and their self-efficacy beliefs in optical teaching and their digital technology use levels were at medium levels. Male teacher candidates achieved significantly higher scores than women in some sub-dimensions of TPACK. It was determined that digital technology usage experience had a strong and significant effect on TPACK levels, optical self-efficacy beliefs and digital technology use. The correlation analysis results revealed that there were positive, medium and high significant relationships between the three variables. Regression analysis showed that optical self-efficacy beliefs and digital technology use together explained 47% of the variance in TPACK levels. In addition, pre-service teachers were grouped into three groups in terms of technology integration. The findings revealed that digital technology experience and field teaching self-efficacy were critical factors in the development of TPACK by pre-service physics teachers. This study contributes to physics education by providing insights into how pre-service teachers' technological competencies and self-efficacy beliefs interact in the context of optics teaching, thereby informing teacher education programs about effective strategies for integrating technology into physics instruction. The research offers important implications that technology integration and field teaching self-efficacy should be developed with a holistic approach in teacher training programs.

Keywords: physics teacher candidates, physics education, use of digital technology, optical teaching, technological pedagogical field knowledge

INTRODUCTION

Optics topics in physics education often involve abstract concepts that are difficult to understand for students. Therefore, the use of digital technologies in optics teaching offers significant opportunities through virtual labs, simulations, and interactive learning materials (Antonio & Castro, 2023; Gamo, 2018). Relevant research shows that digital tools increase student achievement and motivation in teaching optical subjects. Virtual lab tools allow students to perform optical experiments from desktop computers and have the potential to transform traditional teaching practices (Mgeladze & Kapanadze, 2025; von Kotzebue et al.,

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Contribution to the literature

- This study provides the first comprehensive examination of pre-service physics teachers' TPACK competencies specifically focused on optics teaching, addressing a critical gap in subject-specific technology integration research within physics education. A multidimensional framework combining TPACK levels, self-efficacy beliefs toward optics teaching, and digital technology usage patterns was applied to provide a holistic understanding of how these variables interact in the context of a specific and abstract physics domain.
- The findings reveal the relationship between pre-service teachers' technological competencies and their self-efficacy in teaching complex topics like optics, highlighting how technology integration abilities may vary across different content areas within physics education.
- The study contributes empirical evidence on how digital technology experience and subject-specific self-efficacy predict TPACK development, offering insights for designing targeted professional development programs that address both technical skills and pedagogical confidence in teaching challenging physics concepts.

2021). However, the effective use of these technologies depends on teachers' technology integration competencies as well as their domain knowledge (DK) (Casamayou et al., 2025).

In teacher education, it is critical to determine and develop the technological pedagogical content knowledge (TPACK) levels and self-efficacy beliefs of teacher candidates. These competencies directly influence future teaching practices (Joo et al., 2018). Studies show that pre-service teachers' TPACK levels are positively correlated with their self-efficacy beliefs and that these two structures mutually affect each other (Abbitt, 2011; Antonio, 2025). In particular, the examination of the TPACK competencies of pre-service physics teachers is important in terms of the use of discipline-specific technology tools and the integration of pedagogical approaches specific to the subject area. A study by Kim et al. (2024) revealed that pre-service physics teachers exhibited different technology integration patterns in technology integration, which were reflected in their instructional material designs. In this context, the present research aims to comprehensively examine the competencies of pre-service physics teachers in integrating digital technologies in teaching optics subjects.

THEORETICAL FRAMEWORK

Physics Education, Teaching Optics Subjects, and Digital Technologies

Physics education is of great importance in terms of understanding natural phenomena and developing scientific thinking skills. Optics forms an important part of the physics curriculum and covers a wide range of topics, including light, color perception, wave optics, and geometric optics. The teaching of optics subjects stands out as an area that needs to be concretized through the visualization of abstract concepts and experimental studies (Aydin et al., 2012; Juniantari & Suniasih, 2023). Strengthening the pedagogical knowledge (PK) of pre-service physics teachers for teaching optics subjects through technology applications is critical for effective teaching practices (Wahyudi et al., 2022). Research highlights that not only the method but also teacher competencies and beliefs are critical in teaching optics (Antonio, 2025; Oliveira & Bonito 2023). In this context, the relationship between the competencies of physics teacher candidates and student success can be seen more clearly.

Digital technologies offer powerful tools to enrich learning experiences and overcome the limitations of traditional teaching methods in physics education. Notably, computer simulations, virtual labs, data acquisition systems, and interactive learning platforms are widely used in physics teaching (Pokhrel, 2024). These technologies enable students to visualize physical phenomena, perform complex data analysis, and actively participate in experimental processes. Especially in optics education, virtual laboratory tools and simulations allow students to set up complex optical assemblies and test different parameters. Research shows that the use of digital technologies in physics courses increases student motivation, interest, and achievement (Calzada & Antonio, 2011; Gunawan et al., 2018).

Digital tools developed in recent years have been leading to a paradigm shift in physics education. Demonstrations and predetermined laboratory activities that are under the control of teachers in traditional teaching methods are being replaced by interactive simulations and student-centered digital tools (Kang, 2022). This shift aligns with constructivist learning theory and student autonomy emphasized by 21st century skills. Thanks to digital technologies, students can design different experiments and actively build knowledge in order to answer their own questions. The use of mobile technologies in physics education is also a notable area, where measurements can be made and real-time data analysis can be performed using the sensors of smartphones (Zhai et al., 2020). These approaches extend physics education beyond classroom walls and provide students with the opportunity to explore physics concepts in their daily lives. However, effective integration of digital technologies depends on teachers' digitalization-related competencies (Unger & Tracey, 2012; von Kotzebue et al., 2021). The use of discipline-specific technologies in physics education, particularly digital data acquisition systems, requires the integration of pedagogical and DK alongside teachers' technical knowledge (Hoyer & Girwidz, 2020). Research emphasizes the importance of teachers' positive attitudes towards these technologies and high self-efficacy beliefs in order to successfully integrate digital technologies in physics teaching (Keller et al., 2017).

TPACK Competencies of Physics Teacher Candidates

The TPACK framework describes the types of knowledge teachers need for effective integration of technology. TPACK consists of the intersection of technology knowledge (TK), PK, and DK and involves the complex interactions of these knowledge types (Abbitt, 2011; Ay et al., 2015; Mishra & Koehler, 2006). In physics education, TPACK holds particular significance due to its discipline-specific features. Physics teachers need to be able to effectively utilize subject-domain-specific technologies used in experimental studies, such as digital data acquisition systems, simulation software, and visualization tools (Mgeladze & Kapanadze, 2025). A study by Benz and Ludwig (2023) found that the technological knowledge of prospective physics teachers for the use of digital data collection systems falls short in these specific cases. These findings suggest that TPACK needs to be differentiated and measured in discipline-specific contexts. A qualitative study conducted by Kim et al. (2024) examined TPACK expression patterns in innovative teaching materials developed by pre-service physics teachers and identified three different types of technology integration: providing learning materials, providing learning activities, and creating virtual experiments. This study has shown that a strong pedagogical domain knowledge forms the basis for technological pedagogical knowledge and that TK has a strong connection with technological DK.

The role of teaching strategies and learning environments in the development of TPACK competencies of pre-service physics teachers is critical (Willermark, 2017). The screening study by Antonio (2025) examined educational strategies, interventions, and programs to enhance the TPACK competencies of pre-service science teachers. The findings showed that structured approaches, such as technology-integrated metacognitive argumentation-based inquiry, significantly improved pre-service teachers' beliefs about both TPACK and self-efficacy. A recent study by McLay and Reyes (2024) examined the correlations between mathematics and science teachers' perceptions of TPACK with their use of technology and DK, revealing the interactions of these two constructs.

Problem Situation and Gaps of Research

Today, with the digitalization of education systems, the need for technology integration competencies of teachers is increasing. Although the use of digital technologies in physics education, especially in teaching abstract concepts such as optics, offers significant advantages, there is insufficient research on the competencies of pre-service teachers to integrate these technologies effectively. While the current literature focuses on the use of the TPACK framework in physics education, it mostly covers general physics topics and does not delve into TPACK competencies specific to specific subjects (e.g., optics) (Jegstad, 2024; Srisawasdi, 2012). However, a comprehensive examination of pre-service teachers' competencies in integrating digital technologies in optical teaching emerges as an important gap in the literature.

Most of the studies examining the TPACK competencies of pre-service physics teachers do not adequately include their DK or teaching self-efficacy in the research process (Kim et al., 2024; Willermark, 2017). Self-assessment scales measure the perceived knowledge of the participants but do not show how this knowledge is transferred to practice. Furthermore, further research is needed on the relationships between different components of TPACK and how these components interact with the field (Benz & Ludwig, 2023). Some studies show that student teachers, even with high tech knowledge, have difficulties in integrating technology into teaching practice (Fahrurozi et al., 2019; Purwaningsih et al., 2019). This situation reveals that technology integrations should be examined together with the field education variable. Especially in specific subjects such as optics teaching, it is important to evaluate both the subject area-specific TPACK competencies of the teacher candidates and their self-efficacy in teaching this subject together.

Although the role of self-efficacy beliefs in pre-service teachers' instructional practices is generally acknowledged, research on how these beliefs develop and what factors influence them in the context of optics teaching is quite limited. While the existing literature addresses the general self-efficacy beliefs of physics teachers, it does not adequately examine self-efficacy perceptions in specific topics such as optics, which involve complex and abstract concepts in teaching (Martínez-Borreguero et al., 2022). The visual and experimental nature of optics, in particular, requires pre-service teachers to feel competent both in terms of content knowledge and pedagogy. However, there is a lack of systematic studies on which competency areas pre-service teachers perceive themselves as inadequate in this topic and how these inadequacies relate to technology integration (Cai et al., 2021). Furthermore,

Table 1. Demographic characteristics of participants

Variable	Category	Frequency (N)	Percentage (%)
Gender	Female	198	55.6
	Male	158	44.4
Age	18-20 years old	87	24.4
	21-23 years old	156	43.8
	23-25 years old	78	21.9
	Ages 25 and over	35	9.9
Digital technology usage experience	1-3 years	52	14.6
	4-6 years	148	41.6
	7 years and above	156	43.8
Total		**356**	**100**

experimental studies examining the effect of technology use in optics teaching on pre-service teachers' self-efficacy beliefs are quite scarce, and this situation leads to uncertainties about how technology-supported optics teaching practices should be integrated into teacher education processes (Benz & Ludwig, 2023). On the other hand, in-depth research is needed on how self-efficacy beliefs interact with TPACK competencies and how this interaction is reflected in teaching quality, especially in specific physics topics such as optics (Joo et al., 2018).

In the current literature, there are limited studies examining the relationship between pre-service physics teachers' TPACK levels and self-efficacy beliefs, and most of these studies focus on general technology integration (Abbitt, 2011; Joo et al., 2018, Kang, 2022; Kim et al., 2024; Mgeladze & Kapanadze, 2025). Particularly in specific physics subjects such as optics, there is a need for comprehensive research on how pre-service teachers' TPACK competencies and self-efficacy interact and how these variables influence each other (Calzada & Antonio, 2023). The research aims to present findings that will contribute to the development of teacher education programs by analyzing the pre-service teachers' levels of digital technology integration in physics, their self-efficacy in optical teaching, their level of digital technology use in physics and the relationships between these variables.

The sub-problems of the research were determined as follows:

1. What are the physics TPACK levels of physics teacher candidates?
2. What is the level of self-efficacy beliefs of pre-service physics teachers towards optics teaching?
3. What is the level of use of digital technology in physics by pre-service physics teachers?
4. Is there a significant relationship between pre-service physics teachers' physics TPACK levels, self-efficacy beliefs about optics teaching, and digital technology use levels in physics?
5. To what extent do pre-service physics teachers' self-efficacy beliefs about optics teaching and their level of digital technology use in physics predict physics TPACK levels?
6. In which clusters are pre-service physics teachers grouped in terms of physics TPACK levels, self-efficacy beliefs about optics teaching, and levels of digital technology use in physics, and what are the characteristics of these clusters?

METHOD

In this section, information about the model of the research, universe and sample, data collection tools, data collection process and data analysis are included.

Design

This research was carried out within the framework of quantitative research methods and was designed in a descriptive and relational survey model. The descriptive survey model aims to describe and describe a situation as it is, while the relational survey model aims to identify relationships between two or more variables (Creswell & Creswell, 2018).

Study Sample

The population of the research consists of teacher candidates studying in the last year of physics teaching programs at universities in Kazakhstan in the fall semester of the 2025-2026 academic year. The sample of the research was determined using the appropriate sampling method. Convenient sampling is based on the principle that the researcher selects the participants who are most easily accessible for practical reasons such as time, cost, and accessibility (Etikan et al., 2016). In this direction, senior students studying in physics teaching programs of four different universities in different regions of Kazakhstan and accessible to the researcher constituted the sample of the research.

A total of 356 physics teacher candidates participated in the research. The demographic characteristics of the participants are presented in **Table 1**.

According to **Table 1**, 55.6% of the participants were female (n = 198) and 44.4% were male (n = 158). When the age distribution was examined, 24.4% of the participants were 18-20 years old, 43.8% were 21-23 years old, 21.9% were 23-25 years old and 9.9% were 25 years old and over. In terms of digital technology usage experience, 14.6% of the pre-service teachers stated that they had been using digital technologies for 1-3 years, 41.6% for 4-6 years and 43.8% for 7 years or more.

Data Collection Tools

Three different scales were used as data collection tools in the research. These are the "ICT-TPACK-science scale" to measure the physics TPACK levels of pre-service physics teachers, the "optical teaching self-efficacy scale" to measure their self-efficacy beliefs in optics teaching, and the "digital technology use scale in physics" to determine the level of use of digital technologies in physics teaching.

ICT-TPACK-science scale

In order to determine the technological pedagogical field knowledge levels of physics teacher candidates, the "ICT-TPACK-science scale" developed by Kadıoğlu-Akbulut et al. (2020) was used. The scale is designed to assess TPACK competencies for the integration of information and communication technologies into science teaching. The scale consists of 38 items and has a five-factor structure:

(1) planning (8 items),

(2) designing (9 items),

(3) implementation (10 items),

(4) ethics (6 items), and

(5) competence (5 items).

The scale items were graded in a 5-point Likert type (1 = strongly disagree, 5 = strongly agree). In the original development study of the scale, Cronbach's alpha reliability coefficients ranged from .83 to .92 for the sub-dimensions and were reported as .96 for the entire scale. In the present study, the Cronbach's alpha reliability coefficients of the scale were calculated as .89 for the planning dimension, .91 for the design dimension, .90 for the application dimension, .87 for the ethics dimension, .85 for the competence dimension and .96 for the whole scale. These values indicate that the scale is highly reliable.

In the process of adapting the scale to Kazakh, translation and translation were carried out by a team consisting of two linguists and a physics education specialist. Later, the translated scale form was examined by three physics education experts working in Kazakhstan and evaluated for cultural appropriateness. As a result, it was determined that the scale items were understandable and suitable for Kazakh culture.

Optical teaching self-efficacy scale

The "optical teaching self-efficacy scale" developed by Martínez-Borreguero et al. (2022) was used to measure the self-efficacy beliefs of pre-service physics teachers towards teaching optics subjects. The scale assesses pre-service teachers' confidence in teaching subjects such as geometric optics, wave optics, and optical experiments. The scale consists of 28 items and is graded in a 4-point Likert type (1 = I don't trust at all, 4 = I trust completely). The scale has a single-factor structure and all items measure the general self-efficacy beliefs of pre-service teachers towards teaching optics. In the original development study, the Cronbach's alpha reliability coefficient of the scale was reported as .94. In the present study, the Cronbach's alpha reliability coefficient of the scale was calculated as .93.

The process of adapting the scale to Kazakh was carried out by following the same procedure as the ICT-TPACK-science scale. After translation-back translation processes and expert evaluations, it has shown that the scale is suitable and understandable for Kazakh culture.

Digital technology usage scale in physics

In order to determine the level of use of digital technologies in physics teaching by pre-service physics teachers, the "digital technology use scale in physics" was developed by the researcher. The scale development steps recommended by DeVellis (2017) were followed. By reviewing the relevant literature (Becker et al., 2020; Thoms et al., 2023) conceptual framework was created and an 18-item draft article pool covering digital tools used in physics teaching was prepared. The item pool was evaluated in terms of scope validity by a panel consisting of three physics education and two assessment and evaluation experts, and the number of items was reduced to 12 in line with expert opinions. The scale is graded in a 5-point Likert type (1 = never, 5 = always).

The draft scale was piloted on a sample of 224 physics teacher candidates. The KMO value was .91 and the Bartlett test was found to be significant (χ^2 = 1876.43, standard deviation [SD] = 66, $p < .001$). As a result of EFA using principal component analysis and varimax rotation, a single-factor structure was obtained that explained 64.28% of the total variance. Factor load values ranged from .72 to .84, and 2 items with a factor load below .50 were removed from the scale and the scale was reduced to 10 items.

In order to test the construct validity of the scale, CFA was applied by collecting data from a second sample of 189 physics teacher candidates (Byrne, 2016). CFA results have acceptable fit values: χ^2/df = 2.47, RMSEA = .089, CFI = .94, GFI = .91, SRMR = .052. The Cronbach's alpha internal consistency coefficient of the scale was found to be α = .92, and the test-retest reliability was found to be r = .88 ($p < .001$). The scale used in the current research consists of 10 items and has a single-factor structure. High scores indicate that digital technologies

Table 2. Normality analysis results for scales

Scale/subdimension	n	Minimum	Maximum	M	SD	Skewness	Kurtosis
ICT-TPACK-science scale							
Planning	356	1.75	5.00	3.78	0.72	-0.34	-0.28
Designing	356	1.67	5.00	3.65	0.68	-0.29	-0.15
Application	356	1.80	5.00	3.72	0.70	-0.41	0.12
Ethics	356	2.00	5.00	4.12	0.65	-0.58	0.35
Sufficiency	356	1.60	5.00	3.58	0.74	-0.22	-0.19
TPACK total	356	1.95	5.00	3.75	0.62	-0.38	0.08
Optical teaching self-efficacy scale							
Self-efficacy total	356	1.21	4.00	2.84	0.56	-0.15	-0.23
Digital technology usage scale in physics							
Use of digital technology	356	1.80	5.00	3.52	0.79	-0.18	-0.31

are being used more frequently. In the current study, the Cronbach's alpha reliability coefficient of the scale is .93.

Data Collection Process

The data collection process of the research was carried out in the fall semester of the 2025-2026 academic year, between September and October 2025. The data collection tools have been converted into an online survey form using the Google Forms platform. The questionnaire consists of four parts:

(1) demographic information form,

(2) ICT-TPACK-science scale,

(3) optical teaching self-efficacy scale, and

(4) digital technology use scale in physics.

At the beginning of the questionnaire, an "informed consent form" was placed, which gave detailed information to the participants about the purpose of the research, data collection tools and the principle of voluntary participation. Participants confirmed that they voluntarily participated in the study by reading this form before starting the survey.

The link to the online questionnaire form was sent to the pre-service teachers through the faculty members working in the physics teaching programs of the relevant universities. It took about 30-35 minutes to fill out the questionnaire. Throughout the data collection process, the researcher was accessible to answer questions from the participants. Incomplete or incorrectly filled questionnaire forms were excluded from the dataset and a total of 356 valid questionnaire forms were included in the analysis.

Data Analysis

SPSS 28.0 and AMOS 24.0 package programs were used in the analysis of the data collected in the study. Prior to the analysis of the data, various pre-processes were carried out to make the dataset ready for analysis. First, missing data and outlier analyses were performed in the data set. As a result of the lost data analysis, the data of 12 participants with less than 5% lost data in the data set were removed from the analysis by listwise deletion method. For the extreme value analysis, Mahalanobis distance values were calculated and the data of 8 participants exceeding the critical value ($\chi^2 = 77.93$, $p < .001$) were excluded from the analysis.

In order to determine whether the data were normally distributed, skewness and kurtosis coefficients were examined. According to George and Mallery (2020), skewness and kurtosis values in the range of ±2 is an indication that the data are normally distributed. The results of the normality analysis for the scales and sub-dimensions are presented in **Table 2**.

As seen in **Table 2**, all skewness and kurtosis values are in the ±2 range, indicating that the data are normally distributed and it is appropriate to use parametric tests (George & Mallery, 2020). Accordingly, parametric statistical methods were preferred in the analysis of the data.

To answer the research questions, descriptive statistics (mean [M], SD, minimum, and maximum values), independent groups t-test and one-way ANOVA (Tukey HSD test in pairwise comparisons to determine differentiation according to demographic variables), Pearson correlation analysis (to determine the relationship between physics TPACK levels and self-efficacy beliefs about optics teaching), simple linear regression analysis (to determine the relationship between self-efficacy beliefs about optics teaching to determine the predictive power of TPACK levels) and two-stage cluster analysis (to determine the grouping of pre-service teachers in terms of their competence in integrating digital technologies into optics teaching) were used. Bayesian information criterion (BIC) and Silhouette coefficient were considered to determine the optimal number of clusters in cluster analysis. In order to test whether the determined clusters differed significantly in terms of physics TPACK sub-dimensions and optics teaching self-efficacy, one-way MANOVA was applied and one-way ANOVA and post-hoc tests were performed after MANOVA. Effect size values were calculated and reported for significant differences and associations (independent groups Cohen's d for t-test, eta squared for ANOVA, r for correlation analyses, and R^2 for regression analysis).

Table 3. Descriptive statistics on physics TPACK levels of physics teacher candidates

Bottom dimension	n	Minimum	Maximum	M	SD	Level
Planning	356	1.75	5.00	3.78	0.72	High
Designing	356	1.67	5.00	3.65	0.68	High
Application	356	1.80	5.00	3.72	0.70	High
Ethics	356	2.00	5.00	4.12	0.65	High
Sufficiency	356	1.60	5.00	3.58	0.74	Middle
TPACK total	356	1.95	5.00	3.75	0.62	High

Note. Level interpretation: 1.00-2.33 = Low; 2.34-3.66 = Medium; & 3.67-5.00 = High

Table 4. Physics t-test results of TPACK levels by sex

Bottom dimension	Gender	n	M	SD	t	df	p	Cohen's d
Planning	Female	198	3.72	0.74	-1.85	354	.065	-
	Male	158	3.85	0.69				
Designing	Female	198	3.58	0.70	-2.13	354	.034*	0.24
	Male	158	3.74	0.65				
Application	Female	198	3.65	0.72	-2.18	354	.030*	0.23
	Male	158	3.81	0.67				
Ethics	Female	198	4.15	0.63	1.02	354	.309	-
	Male	158	4.08	0.68				
Sufficiency	Female	198	3.51	0.77	-2.06	354	.040*	0.27
	Male	158	3.67	0.70				
TPACK total	Female	198	3.69	0.64	-2.15	354	.032*	0.23
	Male	158	3.82	0.59				

Note. *p < .05

RESULTS

In this section, the findings related to the sub-problems of the research are presented in order.

Findings on the First Sub-Problem

The first sub-problem of the research was expressed as "What are the physics TPACK levels of physics teacher candidates?" In order to find an answer to this sub-problem, descriptive statistics regarding the scores obtained from the ICT-TPACK-science scale were calculated and the results are presented in **Table 3**.

When **Table 3** is examined, it is seen that the mean physics TPACK total score of the physics teacher candidates is 3.75 (SD = 0.62) and this value is at a high level. In terms of sub-dimensions, the highest mean was obtained in the ethics dimension (M = 4.12, SD = 0.65), and the lowest mean was obtained in the competence dimension (M = 3.58, SD = 0.74). While the sub-dimensions of planning (M = 3.78, SD = 0.72), design (M = 3.65, SD = 0.68), and implementation (M = 3.72, SD = 0.70) were all considered high-level, the competence dimension showed a value close to the upper limit of the intermediate level. These findings reveal that pre-service physics teachers are generally at a sufficient level in terms of technological pedagogical field knowledge, but their perception of competence in the use of technology is relatively lower than in other dimensions.

In order to determine whether the physics TPACK levels of the physics teacher candidates differ according to demographic variables, independent groups t-test and one-way ANOVA tests were applied. The results of the independent groups t-test performed according to gender are presented in **Table 4**.

As seen in **Table 4**, a significant difference was found in favor of male teacher candidates in terms of physics TPACK total score ($t = -2.15$, $p = .032$, $d = 0.23$). When the sub-dimensions were examined, significant differences were found in favor of male teacher candidates in the dimensions of design ($t = -2.13$, $p = .034$, $d = 0.24$), implementation ($t = -2.18$, $p = .030$, $d = 0.23$) and competence ($t = -2.06$, $p = .040$, $d = 0.27$). When the effect size values (Cohen's d) are examined, it is seen that all significant differences have small effect sizes. There was no significant difference in the planning and ethics dimensions according to gender ($p > .05$).

A one-way ANOVA test was applied to determine whether the physics TPACK levels of pre-service physics teachers differed according to their experience using digital technology, and the results are presented in **Table 5**.

When **Table 5** is examined, it is seen that the total score of physics TPACK differs significantly according to the experience of using digital technology ($F = 18.74$, $p < .001$, $\eta^2 = .096$). The effect size value ($\eta^2 = .096$) indicates a moderate effect. According to the results of the Tukey HSD post-hoc test, the TPACK scores of teacher candidates with 7 years or more of digital technology use experience were significantly higher than those of candidates with both 1-3 years and 4-6 years of experience. In addition, the TPACK scores of the candidates with 4-6 years of experience were found to be

Table 5. ANOVA results of physics TPACK levels according to digital technology usage experience

Bottom dimension	Source of variance	SS	df	M	F	p	η²	Significant difference
Planning	Between groups	12.68	2	6.34	12.85	.000**	.068	C>A, C>B
	Within groups	174.18	353	0.49				
	Total	186.86	355					
Designing	Between groups	10.42	2	5.21	11.76	.000**	.062	C>A, C>B
	Within groups	156.38	353	0.44				
	Total	166.80	355					
Application	Between groups	14.25	2	7.13	15.42	.000**	.080	C>A, C>B, B>A
	Within groups	163.14	353	0.46				
	Total	177.39	355					
Ethics	Between groups	5.86	2	2.93	7.15	.001**	.039	C>A
	Within groups	144.72	353	0.41				
	Total	150.58	355					
Sufficiency	Between groups	18.74	2	9.37	19.08	.000**	.098	C>A, C>B, B>A
	Within groups	173.26	353	0.49				
	Total	192.00	355					
TPACK total	Between groups	13.85	2	6.93	18.74	.000*	.096	C>A, C>B, B>A
	Within groups	130.52	353	0.37				
	Total	144.37	355					

Note. **$p < .01$; SS: Sum of squares; η^2: Eta squared; A = 1-3 years; B = 4-6 years; C = 7 years and above

Table 6. Descriptive statistics on physics teacher candidates' self-efficacy levels in teaching optics

Scale	n	Minimum	Maximum	M	SD	Level
Teaching optics self-efficacy	356	1.21	4.00	2.84	0.56	Middle

Note. Level interpretation: 1.00-2.00 = Low; 2.01-3.00 = Medium; & 3.01-4.00 = High

Table 7. Optical teaching self-efficacy beliefs t-test results by gender

Gender	n	M	SD	t	df	p	Cohen's d
Female	198	2.79	0.58	-1.64	354	.102	-
Male	158	2.90	0.53				

significantly higher than the candidates with 1-3 years of experience. When the sub-dimensions were examined, significant differences were found in all dimensions of planning, design, implementation, ethics, and competence according to the experience of using digital technology. The highest effect size (η^2 = .098) was observed especially in the proficiency dimension. These findings reveal that the experience of using digital technology significantly affects the TPACK levels of pre-service physics teachers.

Findings on the Second Sub-Problem

The second sub-problem of the research was expressed as "What is the level of self-efficacy beliefs of pre-service physics teachers towards teaching optics subjects?" In order to find an answer to this sub-problem, descriptive statistics regarding the scores obtained from the optical teaching self-efficacy scale were calculated and the results are presented in **Table 6**.

When **Table 6** is examined, it is seen that the mean optical teaching self-efficacy score of the physics teacher candidates is 2.84 (SD = 0.56) and this value is moderate. This finding reveals that the self-confidence of the physics teacher candidates in teaching subjects such as geometric optics, wave optics and optical experiments is at a medium level, but it does not reach a high level.

In order to determine whether the self-efficacy beliefs of pre-service physics teachers differ according to demographic variables, independent groups t-test and one-way ANOVA tests were applied. The results of the independent groups t-test performed according to gender are presented in **Table 7**.

As seen in **Table 7**, there was no statistically significant difference between male and female pre-service teachers in terms of self-efficacy beliefs in optical teaching ($t = -1.64$, $p = .102$). The average scores of both groups are in the intermediate category.

In order to determine whether the self-efficacy beliefs of pre-service physics teachers in optical teaching differ according to their digital technology usage experiences, a one-way ANOVA test was applied and the results were presented in **Table 8**.

When **Table 8** is examined, it is seen that the self-efficacy beliefs of pre-service physics teachers in optics teaching differ significantly according to their experience using digital technology ($F = 15.56$, $p < .001$, $\eta^2 = .081$). The effect size value ($\eta^2 = .081$) indicates a moderate effect. According to the results of the Tukey HSD post-hoc test, the self-efficacy beliefs of pre-service

Table 8. ANOVA results of optical teaching self-efficacy beliefs according to digital technology usage experience

Source of variance	SS	df	MS	F	p	η^2	Significant difference
Between groups	8.94	2	4.47	15.56	.000**	.081	C > A, C > B
Within groups	101.48	353	0.29				
Total	110.42	355					

Note. **p < .01; SS: Sum of squares; MS = Mean of squares; η^2 = Eta squared; A = 1-3 years; B = 4-6 years; & C = 7 years and above

Table 9. Descriptive statistics on digital technology usage levels of physics teacher candidates

Scale	n	Minimum	Maximum	M	SD	Level
Use of digital technology	356	1.80	5.00	3.52	0.79	Middle

Note. Level interpretation: 1.00-2.33 = Low; 2.34-3.66 = Medium; & 3.67-5.00 = High

Table 10. t-test results of digital technology usage levels by gender

Gender	n	M	SD	t	df	p	Cohen's d
Female	198	3.45	0.82	-1.78	354	.076	-
Male	158	3.61	0.75				

Table 11. ANOVA results of digital technology usage levels according to digital technology usage experience

Source of variance	SS	df	MS	F	p	η^2	Significant difference
Between groups	32.84	2	16.42	30.84	.000**	.149	C > A, C > B, B > A
Within groups	188.01	353	0.53				
Total	220.85	355					

Note. **p < .01; SS: Sum of squares; MS = Mean of squares; η^2 = Eta squared; A = 1-3 years; B = 4-6 years; & C = 7 years and above

teachers with 7 years or more of digital technology use experience were significantly higher than those of candidates with both 1-3 years and 4-6 years of experience. These findings reveal that with the increase in digital technology usage experience, pre-service teachers' self-efficacy beliefs in teaching optics subjects also strengthen.

Findings on the Third Sub-Problem

The third sub-problem of the research was expressed as "What is the level of use of digital technologies in physics teaching by pre-service physics teachers?" In order to find an answer to this sub-problem, descriptive statistics regarding the scores obtained from the digital technology use scale in physics were calculated and the results were presented in **Table 9**.

When **Table 9** is examined, it is seen that the mean level of use of digital technologies in physics teaching by pre-service physics teachers is 3.52 (SD = 0.79) and this value is close to the upper limit of the intermediate level. This finding shows that pre-service physics teachers use digital technologies such as physics simulation software, virtual laboratory tools, interactive applications, digital data acquisition systems, and online physics resources moderately.

In order to determine whether the digital technology usage levels of pre-service physics teachers differ according to demographic variables, independent groups t-test and one-way ANOVA tests were applied. The results of the independent groups t-test performed according to gender are presented in **Table 10**.

As seen in **Table 10**, there was no statistically significant difference between male and female teacher candidates in terms of the levels of digital technology use in physics teaching ($t = -1.78$, $p = .076$). The average scores of both groups are in the intermediate category.

A one-way ANOVA test was applied to determine whether the digital technology usage levels of physics teacher candidates differed according to their digital technology usage experiences and the results are presented in **Table 11**.

When **Table 11** is examined, it is seen that the digital technology usage levels of pre-service physics teachers differ significantly according to their digital technology usage experience ($F = 30.84$, $p < .001$, $\eta^2 = .149$). The effect size value ($\eta^2 = .149$) indicates a large level of effect. According to the results of the Tukey HSD post-hoc test, the digital technology usage levels of teacher candidates with 7 years or more of digital technology use experience were significantly higher than those of candidates with both 1-3 years and 4-6 years of experience. In addition, the digital technology usage levels of candidates with 4-6 years of experience were found to be significantly higher than those of candidates with 1-3 years of experience. These findings reveal that with the increase in digital technology usage experience, the frequency of teacher candidates' use of digital technologies in physics teaching has increased significantly.

	1. Planning	2. Design	3. Application	4. Ethics	5. Competence	6. TPACK Total	7. Optics Self-Efficacy	8. Digital Tech Use
1. Planning	1.00	0.78	0.81	0.65	0.74	0.89	0.56	0.62
2. Design	0.78	1.00	0.83	0.68	0.79	0.92	0.61	0.68
3. Application	0.81	0.83	1.00	0.71	0.82	0.94	0.64	0.71
4. Ethics	0.65	0.68	0.71	1.00	0.69	0.80	0.48	0.52
5. Competence	0.74	0.79	0.82	0.69	1.00	0.91	0.67	0.74
6. TPACK Total	0.89	0.92	0.94	0.80	0.91	1.00	0.68	0.75
7. Optics Self-Efficacy	0.56	0.61	0.64	0.48	0.67	0.68	1.00	0.71
8. Digital Tech Use	0.62	0.68	0.71	0.52	0.74	0.75	0.71	1.00

Figure 1. Correlation matrix (Source: Authors' own elaboration)

Findings on the Fourth Sub-Problem

The fourth sub-problem of the study was expressed as "Is there a significant relationship between the physics TPACK levels of pre-service physics teachers, their self-efficacy beliefs about optics teaching and their level of digital technology use in physics?". Pearson correlation analysis was performed to find an answer to this sub-problem and the results are presented in **Figure 1**.

According to **Figure 1**, there are positive, medium and high significant relationships between the three main variables of the research, TPACK level, optical teaching self-efficacy belief and digital technology use. A moderately significant relationship was found between the TPACK scores of the physics teacher candidates and their self-efficacy in optical teaching ($r = .68$, $p < .01$). In addition, a high level of positive correlation was observed between TPACK and digital technology use ($r = .75$, $p < .01$). The relationship between optical self-efficacy and digital technology use is also high and significant ($r = .71$, $p < .01$). Strong relationships were observed between the use of digital technology and TPACK sub-dimensions at the sub-dimensions level; the highest relationship was determined as competence ($r = .74$) and the lowest relationship was determined as ethics ($r = .52$). In general, the findings show that pre-service physics teachers' TPACK, self-efficacy in optical teaching, and the use of digital technology form a holistic structure that positively affects each other.

Findings on the Fifth Sub-Problem

The fifth sub-problem of the research was expressed as "To what extent do pre-service physics teachers' self-efficacy beliefs about optics teaching and their level of digital technology use in physics predict physics TPACK levels?" Multiple linear regression analysis was performed to find an answer to this sub-problem. In the analysis, Physics TPACK total score was included as the dependent variable, and optical teaching self-efficacy beliefs and digital technology usage levels were included as independent variables. Before the regression analysis, variance inflation factor (VIF) and tolerance values were examined to check whether there was a multicollinearity problem. VIF values less than 10 (VIF < 2.5) and Tolerance values greater than 0.10 (tolerance > .40) indicated that there was no multi-junction problem. The results of the regression analysis are presented in **Table 12**.

When **Table 12** is examined, it is seen that self-efficacy beliefs and digital technology use levels in optical teaching together significantly predict physics TPACK levels ($F = 357.24$, $p < .001$). When the explanatory power of the model ($R^2 = .47$) is examined, it is seen that these two independent variables together explain 47% of the total variance in physics TPACK levels. The adjusted R^2 value (.47) supports the same result. When the standardized regression coefficients (β) are examined, it is seen that the level of digital technology use ($\beta = .46$, $p < .001$) is a stronger predictor

Table 12. Multiple regression analysis results on optical self-efficacy beliefs and digital technology use's prediction of physics TPACK levels

Model	Independent variable	B	Standard error	β	t	p	Dual r	Partial r
	Constant	0.98	0.12	-	8.17	.000	-	-
1	Optical self-efficacy	0.42	0.05	.38	8.84	.000	.68	.43
	Use of digital technology	0.36	0.03	.46	10.67	.000	.75	.49

	R	R^2	Adjusted R^2	F	p
1	.62	.47	.47	357.24	.000**

Note. **p < .01 & Dependent variable: TPACK total score

on the physics TPACK, followed by self-efficacy beliefs in optical teaching (β = .38, p < .001). Both independent variables make a significant and unique contribution to the model.

When the pairwise correlations (binary r) and partial correlations (partial r) were examined, the pairwise correlation (r = .75) and partial correlation (r = .49) of digital technology use with TPACK were found to be higher than that of optical self-efficacy (r = .68 and r = .43, respectively). This suggests that the impact of digital technology use on TPACK is more pronounced. The regression equation can be expressed as follows:

$$TPACK\ total\ score = 0.98 + (0.42 \times optical\ self-efficacy\ score) + (0.36 \times digital\ technology\ usage\ score). \quad (1)$$

These findings reveal that pre-service physics teachers' self-efficacy beliefs in teaching optics subjects and their level of using digital technologies in physics teaching are strong predictors of TPACK levels. In particular, it is seen that the experience of using digital technology has a more decisive role on TPACK levels.

Findings on the Sixth Sub-Problem

The sixth sub-problem of the research was expressed as "In which clusters are pre-service physics teachers grouped in terms of physics TPACK levels, self-efficacy beliefs towards optics teaching and digital technology use levels in physics, and what are the characteristics of these clusters?". In order to find an answer to this sub-problem, two-stage cluster analysis was performed. In the cluster analysis, ICT-TPACK-science scale total score, optical teaching self-efficacy scale score and digital technology use in physics scale score were included in the model as independent variables.

BIC and Silhouette coefficient were used to determine the optimal number of clusters. The results of the analysis showed that three clusters were the most appropriate solution (BIC = 1247.82, Silhouette = 0.58). The quality evaluation of the three clusters was found to be at the level of "good". The sizes and proportions of the clusters are presented in **Table 13**.

When **Table 13** is examined, 21.9% (n = 78) of the participants were in the low integration group, 46.3% (n = 165) in the medium integration group and 31.7% (n = 113) in the high integration group. It is seen that the largest group is the middle integration group. In order

Table 13. Distribution of groups formed as a result of cluster analysis

Set	n	%
Cluster 1. Low integration group	78	21.9
Cluster 2. Medium integration group	165	46.3
Cluster 3. High integration group	113	31.7
Total	356	100

to test whether the determined clusters differ significantly in terms of physics TPACK sub-dimensions, optics teaching self-efficacy and digital technology use, one-way MANOVA was first applied. MANOVA results showed that the clusters differed significantly in terms of all dependent variables (Wilks' lambda = .186, F = 68.42, p < .001, partial η^2 = .52). This finding shows that the cluster analysis was performed successfully and the groups were significantly separated from each other.

After MANOVA, one-way ANOVA and post-hoc tests were performed for each dependent variable and the results are presented in **Table 14**.

When **Table 14** is examined, it is seen that there are significant differences between the three clusters in terms of all variables (p < .001). According to the results of the Tukey HSD post-hoc test, significant differences were found in all variables as cluster 3 > cluster 2 > cluster 1. When the effect size values (η^2) are examined, it is seen that all differences have a large impact (between η^2 = .337 and η^2 = .558).

Characteristic features of clusters

Cluster 1 (low integration group, n = 78, 21.9%): Pre-service teachers in this group had the lowest scores in terms of physics TPACK (M = 2.99, SD = 0.48), optics teaching self-efficacy (M = 2.21, SD = 0.42) and digital technology use (M = 2.58, SD = 0.54). Of the TPACK sub-dimensions, only ethics (M = 3.52) was moderate, while the other dimensions were low-moderate. This group consists of pre-service teachers who have insufficient competence and low self-confidence in integrating digital technologies into optics teaching, and who rarely use digital tools.

Cluster 2 (intermediate integration group, n = 165, 46.3%): Pre-service teachers in this group had moderate scores in terms of physics TPACK (M = 3.64, SD = 0.44), self-efficacy in optical teaching (M = 2.78, SD = 0.38) and use of digital technology (M = 3.41, SD = 0.52). While

Table 14. Comparison of clusters in terms of physics TPACK sub-dimensions, optical self-efficacy, and digital technology use

Variable	M (SD)			F	p	η^2	Significant difference
	Cluster 1 (n = 78)	Cluster 2 (n = 165)	Cluster 3 (n = 113)				
Planning	2.98 (0.54)	3.65 (0.52)	4.42 (0.41)	178.63	.000**	.503	3 > 2 > 1
Designing	2.87 (0.51)	3.52 (0.48)	4.29 (0.38)	195.47	.000**	.525	3 > 2 > 1
Application	2.94 (0.56)	3.58 (0.51)	4.35 (0.42)	183.28	.000**	.510	3 > 2 > 1
Ethics	3.52 (0.61)	4.08 (0.52)	4.58 (0.38)	89.74	.000**	.337	3 > 2 > 1
Sufficiency	2.76 (0.58)	3.42 (0.54)	4.21 (0.46)	156.82	.000**	.470	3 > 2 > 1
TPACK total	2.99 (0.48)	3.64 (0.44)	4.36 (0.35)	223.18	.000**	.558	3 > 2 > 1
Optical self-efficacy	2.21 (0.42)	2.78 (0.38)	3.38 (0.35)	174.56	.000**	.497	3 > 2 > 1
Use of digital technology	2.58 (0.54)	3.41 (0.52)	4.28 (0.48)	192.83	.000**	.522	3 > 2 > 1

Note. **p < .01 & η^2 = Eta squared

ethics (M = 4.08) was high in the TPACK sub-dimensions, the other dimensions were moderate. This group, which makes up about half of the participants, consists of teacher candidates who can use digital technologies at a moderate level and have the potential to develop with targeted interventions.

Cluster 3 (high integration group, n = 113, 31.7%): Pre-service teachers in this group had the highest scores in terms of physics TPACK (M = 4.36, SD = 0.35), optical teaching self-efficacy (M = 3.38, SD = 0.35) and digital technology use (M = 4.28, SD = 0.48). The TPACK sub-dimensions are all at a high level. This group consists of pre-service teachers who can integrate digital technologies into optics teaching at an advanced level, have high self-confidence and use digital tools frequently and effectively.

Figure 2 shows the cluster distribution of preservice physics teachers.

Chi-square test was applied to examine the distribution of clusters according to demographic variables and the results are presented in **Table 15**.

When **Table 15** is examined, it is seen that the clusters do not differ significantly in terms of gender (χ^2 = 2.84, p = .242). However, significant differences were found between the clusters in terms of digital technology usage experience (χ^2 = 87.45, p < .001). While 53.8% of the teacher candidates with 1-3 years of experience were in the low integration group, 51.9% of the candidates with 7 years or more of experience were in the high integration group. This finding suggests that digital technology usage experience significantly influences the clustering structure, and as experience increases, pre-service teachers are more likely to be in higher integration groups.

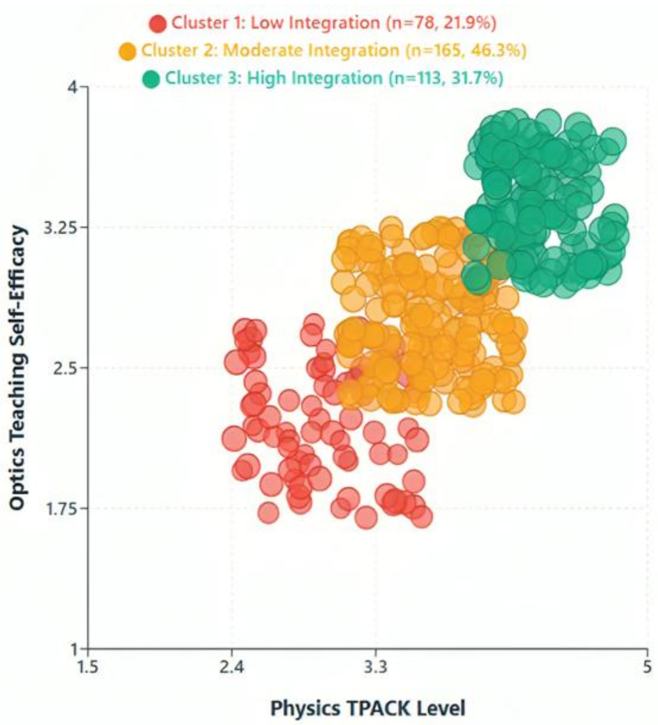

Figure 2. Cluster distribution of preservice physics teachers (Source: Authors' own elaboration)

DISCUSSION

In this study, the relationships between pre-service physics teachers' TPACK levels, self-efficacy beliefs about optics teaching and digital technology usage levels were examined. Within the scope of the first sub-problem of the research, it was determined that the TPACK levels of the physics teacher candidates were generally high. This finding shows that the pre-service

Table 15. Distribution of clusters by demographic variables

Column 1	Category	Cluster 1: n (%)	Cluster 2: n (%)	Cluster 3: n (%)	χ^2	p
Gender	Female	48 (24.2)	94 (47.5)	56 (28.3)	2.84	.242
	Male	30 (19.0)	71 (44.9)	57 (36.1)		
Digital technology usage experience	1-3 years	28 (53.8)	20 (38.5)	4 (7.7)	87.45	.000**
	4-6 years	38 (25.7)	82 (55.4)	28 (18.9)		
	7 years and above	12 (7.7)	63 (40.4)	81 (51.9)		

Note. **p < .01

teachers' competence to use technology, pedagogy and field knowledge in an integrated manner is at a satisfactory level. When the sub-dimensions are examined, obtaining the highest average in the ethics dimension reveals that pre-service teachers have a strong awareness of the responsible, safe and ethical use of digital technologies. In addition, the fact that the proficiency dimension remains at the upper limit of the intermediate level indicates that teacher candidates should continue to improve their technological competencies. Mgeladze and Kapanadze (2025) highlighted that TPACK integration in physics education enhances technological proficiency. The findings in this study support the need to systematically develop technology usage skills in the pre-service period. Similarly, Kim et al. (2024) note that student teachers exhibit varying levels of proficiency in different dimensions of TPACK when designing innovative physics teaching materials.

In the analyzes made according to the gender variable, it was observed that male teacher candidates achieved significantly higher scores than women in the TPACK total scores and design, implementation and competence sub-dimensions. This finding may reflect the impact of gender roles in technology use and potential differences in opportunities to access technology. McLay and Reyes (2024) have highlighted the importance of affective factors beyond TPACK, emphasizing the need to consider individual differences in technology-rich learning environments. The fact that there is no significant difference in terms of gender in the dimensions of planning and ethics shows that male and female teacher candidates have similar levels of competence in areas such as pedagogical planning and ethical sensitivity. This situation reveals that the basic pedagogical competencies required by the teaching profession can be acquired regardless of gender.

The effect of digital technology usage experience on TPACK levels is one of the most striking findings of the research. Teacher candidates with seven years or more of digital technology experience had significantly higher TPACK scores compared to their less experienced peers, highlighting the importance of technology engagement time. This finding suggests that experience in technology use is a cumulative learning process and that long-term interaction with technology strongly supports TPACK development. Benz and Ludwig (2023) highlighted the strong correlation between pre-service physics teachers' proficiency in using digital data collection systems and general technological knowledge, emphasizing the critical role of the experience factor. Similarly, Fahrurozi et al. (2019) have stated that technological experience is a fundamental component in the development of TPACK in vocational education. These findings reveal that teacher training programs should provide teacher candidates with systematic and intensive interaction opportunities with various digital technologies from the early stages. Moreover, Bekoe et al. (2025) explored how teacher characteristics influence technological self-efficacy within Ghana's standard-based curriculum, surveying 280 in-service teachers through an explanatory sequential mixed-method design. The study found that teacher-student interaction characteristics and humanistic and justice characteristics significantly predicted various aspects of teachers' technological self-efficacy. Qualitative findings established how these characteristics manifested in classroom practices, highlighting the importance of interactive methods and empathy in fostering student engagement and technological competence. Bekoe et al. (2025) concluded that enhancing teachers' technological self-efficacy requires a holistic approach, integrating technical skills with humanistic values to create inclusive and effective learning environments. This underscores the need for tailored professional development programs that address varying levels of technological self-efficacy among teachers, complementing the emphasis on sustained digital technology experience in TPACK development.

Within the scope of the second sub-problem of the research, it was determined that the self-efficacy beliefs of the physics teacher candidates towards optics teaching were at a moderate level. This finding shows that pre-service teachers' self-confidence in teaching subjects such as geometric optics, wave optics, and optical experiments is sufficient but open to improvement. Aydin et al. (2012) determined that pre-service science teachers had misconceptions about geometric optics. This may explain why pre-service teachers' self-efficacy beliefs remain at a moderate level. The abstract and conceptually challenging nature of optics subjects can impact pre-service teachers' confidence in teaching them. Wahyudi et al. (2022) stated that problem-solving-based optics modules improve pre-service teachers' higher-order thinking skills. This situation has revealed the importance of pedagogical approaches in developing self-efficacy for optics teaching. The fact that there is no significant difference in optical teaching self-efficacy beliefs according to the gender variable shows that male and female teacher candidates have a similar level of competence perception in this special field knowledge.

The moderate level of use of digital technology in physics teaching shows that pre-service teachers are willing to use physics simulation software, virtual laboratory tools and interactive applications, but they have not yet routinely integrated these tools. Pokhrel (2024), in his study examining the applications and challenges of digital technologies in physics education, drew attention to the obstacles faced by teachers in technology integration; This may explain why pre-service teachers exhibit moderate use. The large impact size of the digital technology usage experience on the level of use reveals that experience is a critical factor not only in the development of TPACK, but also in the use of technology in real classroom settings. Gamo (2018) and Casamayou et al. (2025) have demonstrated that the use of virtual lab and interactive digital simulations in optical experiments improves learning outcomes. This finding highlights the potential of digital technology use in physics teaching. The fact that there is no significant difference in the use of digital technology according to the gender variable suggests that access to technology and usage opportunities are similar for both genders.

The strong positive relationships between TPACK levels, optical teaching self-efficacy beliefs and digital technology use, which emerged in the fourth sub-problem of the research, show that these three structures mutually support each other. The high level of positive relationship between TPACK and the use of digital technology highlights the importance of practical technology use in the development of technological pedagogical DK. Abbitt (2011) examined the relationship between pre-service teachers' self-efficacy beliefs about technology integration and TPACK and found a similarly strong relationship. The high relationship between optical self-efficacy and digital technology use suggests that confidence in field knowledge encourages technology use or that technology use increases confidence in field teaching. Joo et al. (2018) stated that teacher self-efficacy is an important factor affecting the intention to use technology. At the level of sub-dimensions, the competence dimension has the highest relationship with the use of digital technology, revealing that the development of technological skills is directly related to the frequency of technology use.

The results of the regression analysis showed that optical teaching self-efficacy beliefs and digital technology use levels together explained 47% of the variance in TPACK levels. This strong explanation rate reveals that these two variables are critical factors in the development of TPACK of pre-service physics teachers. The fact that the use of digital technology is a stronger predictor on TPACK shows that active interaction with technology is more decisive than theoretical knowledge. Antonio (2025), in his comprehensive review examining the impact of instructional strategies, interventions, and programs on pre-service science teachers' TPACK development, emphasized that hands-on technology experiences are indispensable for TPACK development. Keller et al. (2017) showed the effect of physics teachers' pedagogical content knowledge on student achievement; the findings of this study support that the development of TPACK should be a priority goal in teacher education. Willermark (2017), in his review of empirical studies on TPACK, pointed out the necessity of multifactorial approaches in TPACK development; The regression model of the present study supports this multifactorial approach with concrete data.

The results of the two-stage cluster analysis revealed that the physics teacher candidates were clustered in three different groups in terms of Physics TPACK levels, optics teaching self-efficacy beliefs and digital technology usage levels. 21.9% of the participants were in the clusters called low integration group, 46.3% in the medium integration group and 31.7% in the high integration group. This finding indicates the presence of significant heterogeneity among pre-service teachers in terms of technology integration competencies, aligning with the study by Kim et al. (2024), which highlighted individual differences in pre-service physics teachers' TPACK competencies. Notably, the largest group was the intermediate integration group, indicating that while the majority of pre-service teachers possess basic competencies in technology integration, there is potential for further development of these competencies. To enhance technological proficiency in physics education, integrating TPACK with cooperative learning can be an effective approach to realizing this potential, as highlighted by Mgeladze and Kapanadze (2025). The significant differentiation of the clusters in terms of all variables and the obtaining of large effect size values indicate that the cluster analysis was performed successfully and the characteristic features of the groups were clearly differentiated.

Implications of the Findings

The findings of this research offer important implications for teacher training programs. First, training opportunities for the use of digital technology in programs should be provided to support the TPACK development of physics teacher candidates. In particular, the relatively low proficiency dimension shows that laboratory and micro-teaching practices should be increased in order for teacher candidates to gain hands-on experience with various technology tools. It indicates that self-efficacy beliefs in optics teaching should remain at a moderate level, and special pedagogical strategies, simulation tools and trainings for eliminating conceptual misconceptions should be integrated into the program for teaching optics subjects. The strong impact of digital technology usage experience on TPACK and self-efficacy emphasizes the importance of teacher candidates interacting with technology from the first years of their undergraduate education. In addition, providing equal opportunities to all teacher candidates in areas where gender-based differences are observed and democratizing access to technology are necessary for an inclusive approach in TPACK development.

Limitations

This research has some limitations. First, the study is a cross-sectional survey study based on the quantitative research method, and it is limited in explaining the causal relationships between the variables. However, the data were collected through self-report scales, and there is a possibility that the participants showed a tendency towards social liking. In addition, the research is limited to pre-service physics teachers, and the findings may not be generalized to pre-service teachers of other branches. Another limitation is the focus of the research on optics. This limits the direct generalization of the findings to other topics of physics education (such as mechanics, electricity, modern physics). Digital technology experience is measured by the number of years reported and does not provide detailed information on the nature and diversity of experience. Finally, since the research was carried out over a specific time period, the changes in TPACK development of pre-service teachers were not examined longitudinally.

Recommendations

Based on the research findings, various suggestions can be made for future research and applications. In future research, studies that examine TPACK development longitudinally should be designed and the changes in TPACK levels of pre-service teachers during their undergraduate education and the factors affecting this change should be examined in detail. Using mixed methods research, pre-service teachers' TPACK development processes, experiences in the use of technology and the formation of self-efficacy beliefs should be investigated in depth with qualitative data. Through experimental and quasi-experimental studies, the effectiveness of TPACK and specific intervention programs to improve self-efficacy should be tested. In teacher training programs, courses that systematically use innovative technologies such as simulation-based teaching, virtual laboratory applications and augmented reality should be developed to improve the technology integration skills of physics teacher candidates. Special pedagogical trainings, peer teaching practices and micro-teaching sessions can be organized to increase optics teaching self-efficacy. In addition, all teacher candidates should be provided with equal access and opportunities to use technology and supportive learning environments should be created to reduce gender-based differences.

CONCLUSION

As a result of this research, it was determined that the TPACK levels of physics teacher candidates were generally high; and the level of self-efficacy beliefs and digital technology use of optics teaching was at a medium level. The strong impact of digital technology usage experience on both TPACK and self-efficacy suggests that early and intensive interaction with technology is critical in teacher education. The strong predictor of optical self-efficacy and the use of digital technology suggests that these three structures mutually support each other and should be developed with a holistic approach. Observing some gender-based differences emphasizes the necessity of inclusive teacher training approaches. In this context, the integrated development of TPACK, field teaching self-efficacy and the use of digital technology in the training of 21st century physics teachers is indispensable for effective and contemporary physics teaching. The findings of this research provide important information for the design and implementation of teacher training programs and provide a guiding framework for future research.

Author contributions: All authors contributed equally to conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing—original draft, writing—review and editing, visualization, supervision, and project administration. All authors have read and approved the final version of the manuscript and agreed with the results and conclusions.

Funding: No funding source is reported for this study.

Acknowledgements: Indira B. Usembayeva acknowledges the support of the Khoja Akhmet Yassawi International Kazakh-Turkish University Associate Professor–Researcher Program and Ulbosyn A. Abitayeva acknowledges her gratitude to the Chairperson of the Board – Rector of Korkyt Ata Kyzylorda University.

Ethical statement: The authors stated that ethical approval for this study was obtained from the Ethics Committee of Korkyt Ata Kyzylorda State University. All research procedures were conducted in accordance with the ethical standards of the institution and the principles of the Declaration of Helsinki.

AI statement: The authors stated that no generative artificial intelligence tools or AI-based software were used in the design, data collection, analysis, or writing of this study.

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.

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