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An examination of pre-service science teachers' technological pedagogical content knowledge and self-directed learning skills with technology

Hacı Mehmet Yeşiltaş [1], **Erol Taş** [1]

[1] Faculty of Education, Ordu University, Ordu, Türkiye

ABSTRACT

This study investigates pre-service science teachers' Technological Pedagogical Content Knowledge (TPACK) and their Self-Directed Learning with Technology (SDL-T) abilities by examining how these competencies vary in relation to several demographic and technology-related factors. SDL-T refers to individuals' capacity to organize, monitor, and evaluate their own learning processes using digital tools, while TPACK represents teachers' integrated knowledge of pedagogy, subject matter, and technology. Both constructs are considered key qualifications for future science educators who are expected to design innovative, technology-enhanced learning environments. The research employs a relational survey model to explore the participants' TPACK and SDL-T levels and to determine whether these constructs differ across grade level, academic achievement, frequency of technology use, and technological tendencies. The study group consisted of 79 pre-service science teachers enrolled in the 2nd, 3rd, and 4th years of a state university's science teacher education program. Data were collected through the TPACK Self-Efficacy Scale and the SDL-T Scale. Findings showed that although scores increased as grade level and GPA rose, neither variable produced statistically significant differences in TPACK or SDL-T. In contrast, both the frequency of technology use and participants' inclination toward digital tools led to significant variations in the two constructs. The results indicate that personal interest in technology and active digital engagement are stronger determinants of TPACK and SDL-T than traditional academic indicators such as GPA or year of study. By simultaneously examining these two constructs, which are often addressed separately, this study provides new empirical evidence suggesting that fostering positive technological dispositions may be more critical than grade-level progression in pre-service teacher education.

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CORRESPONDENCE

Hacı Mehmet Yeşiltaş

Introduction

In the rapidly evolving landscape of information and communication technologies today, the skills required of educators extend beyond traditional teaching paradigms. For technology to be utilized effectively in instructional settings, teachers must possess not only technical competencies but also an integrated understanding that merges technology, pedagogy, and content expertise. The Technological Pedagogical Content Knowledge (TPACK) framework addresses this need by providing a holistic structure that defines an educator's capacity to integrate technology effectively for educational ends. The main goal of TPACK is to build teachers' capability to concurrently apply their subject matter knowledge, instructional methods, and technological instruments

However, in the digital age, it is not sufficient for pre-service teachers to merely have access to technology; they must also be able to use technology to direct and regulate their own learning. In this context, the concept of Self-Directed Learning with Technology (SDL-T) encompasses individuals' abilities to set learning goals, select appropriate resources, monitor their progress, and evaluate outcomes using technological tools. Self-directed learning is considered an essential component that supports pre-service teachers' lifelong learning skills. A review of the literature emphasizes that individuals who use technology as a self-regulatory learning tool tend to have higher levels of academic achievement, motivation, and autonomy toward learning (Barnard-Brak et al., 2010; Panadero, 2017). This suggests that pre-service teachers should not only be consumers of knowledge but also active producers and managers of their own learning processes. Therefore, technology integration in teacher education should be addressed together with the development of self-directed learning skills, supporting pre-service teachers' effective use of digital tools in planning, implementation, and reflection processes (Zimmerman, 2008; Lai, 2015).

Developing both the TPACK levels and SDL-T skills of pre-service science teachers is crucial for ensuring the sustainability of innovative and effective teaching practices in future learning environments. Variables such as the frequency of technology use, attitudes toward technology, academic achievement, and grade level may influence the development of these two constructs. The literature highlights that pre-service teachers' ability to effectively use technology for pedagogical purposes depends not only on technical knowledge but also on their capacity to manage the interaction between pedagogical, content, and technological knowledge domains (Mishra & Koehler, 2006; Chai et al., 2013). Accordingly, the TPACK framework plays a critical role in enabling pre-service teachers to transform technological tools into meaningful learning experiences.

Moreover, pre-service teachers' SDL-T skills allow them to use digital tools effectively to learn independently, access information, and set personal learning goals (Lai, 2015; Zimmerman, 2008). The simultaneous development of these two constructs helps pre-service teachers gain both pedagogical and cognitive flexibility, enabling them to take more active roles in blended learning and AI-supported educational environments (Koehler et al., 2019). Therefore, teacher education programs focusing on technology integration should not only aim to improve technical skills but also emphasize self-regulation, critical thinking, and lifelong learning attitudes.

The ability of pre-service teachers to use technology meaningfully and pedagogically forms the foundation of sustainable innovation in education. The combined development of TPACK and SDL-T skills enhances pre-service teachers' ability to effectively use digital tools while independently managing their own learning processes. This shift contributes to transforming teachers from passive transmitters of knowledge into active designers and facilitators of learning.

Despite the growing body of research emphasizing the importance of both Technological Pedagogical Content Knowledge (TPACK) and Self-Directed Learning with Technology (SDL-T) in teacher education, several gaps remain evident in the existing literature. First, while numerous studies have examined TPACK or self-directed learning skills independently, research that simultaneously investigates these two constructs within the same empirical framework remains limited, particularly among pre-service science teachers. This limitation restricts a comprehensive understanding of how pedagogical technology integration and self-regulated technology use interact in shaping teachers' professional competencies. Second, variables related to technological predisposition and frequency of technology use have often been treated as secondary or descriptive factors, rather than being systematically analyzed as potential determinants of both TPACK and SDL-T development. Moreover, existing studies frequently focus on general teacher populations or specific subject areas, leaving pre-service science teachers underrepresented, despite the discipline's strong reliance on technology-supported inquiry and experimentation. Addressing these gaps is essential for advancing teacher education research and for designing programs that holistically support pre-service teachers' pedagogical and self-directed learning competencies in technology-rich learning environments.

The purpose of this study is to examine the effects of various variables on pre-service science teachers' SDL-T and TPACK levels. In this context, the study seeks to answer the following research questions:

1. What are the levels of pre-service science teachers' SDL-T and TPACK?
2. How do the levels of pre-service science teachers' SDL-T and TPACK vary according to Grade Point Average (GPA), grade level, frequency of technology use, and tendency toward technological tools?

Method

This study was conducted using relational survey design, one of the quantitative research approaches frequently used to examine the relationships between variables within a specific group. Survey designs are typically preferred when the objective is to identify individuals' perceptions, attitudes, and behaviors related to a particular phenomenon. In a relational survey model, the main purpose is to determine whether variables are associated and to what extent these associations occur (Creswell, 2012; Bekman, 2022). For this study, the relational survey model was selected to examine pre-service science teachers' scores on the TPACK and SDL-T scales and to reveal how these scores differ across various demographic and technology-related variables.

Participants

The study group was identified through a simple random sampling strategy, which ensures that each member of the population has an equal and independent chance of being selected (Canbazoğlu Bilici, 2019). Simple random sampling was carried out by generating a randomized list of enrolled pre-service science teachers and selecting participants using a random number generator, ensuring equal selection probability. The sample consisted of 79 pre-service science teachers enrolled in the 2nd, 3rd, and 4th years of a science education program at a state university. The sample was considered appropriate for the aims of the study as it allowed the researchers to gather data from individuals at different stages of their undergraduate training.

Data collection tools

Two standardized instruments were used for data collection: the TPACK Self-Efficacy Scale and the Self-Directed Learning with Technology Scale. Both scales demonstrated acceptable reliability levels within this study (α > .80), consistent with psychometric thresholds.

TPACK Self-Efficacy Scale (TPACKS)

The Technological Pedagogical Content Knowledge (TPACK) Self-Efficacy Scale, originally developed by Balçın and Ergün (2016), includes 40 items structured across eight sub-dimensions. The instrument evaluates pre-service teachers' perceived competence in integrating technology with pedagogy and content knowledge. While the original study reported a Cronbach's alpha coefficient of .93, reliability analysis conducted in the present research yielded an internal consistency value of .87.

Self-Directed Learning with Technology Scale (SDL-TS)

To assess participants' competence in self-regulating their learning through digital tools, the Self-Directed Learning with Technology Scale developed by Teo et al. (2010) and adapted into Turkish by Tercan, Horzum, and Uysal (2014) was used. The scale consists of 6 items organized into two sub-dimensions. The reliability coefficients reported in earlier studies were .87 for the original version and .77 for the Turkish adaptation. In the current research, the scale demonstrated a Cronbach's alpha of .81, indicating acceptable reliability.

Both instruments were administered electronically but completed in face-to-face classroom settings to provide guidance and ensure accurate responses.

Data collection and analysis

Data were collected during the 2024–2025 spring semester from students enrolled in the science teacher education program. Participation was voluntary, and before completing the instruments, participants received a detailed explanation of the study's purpose and procedures.The dataset was analyzed using SPSS. Skewness and kurtosis values for both scales were examined to determine whether the data followed a normal distribution. Since all values were within the acceptable range of −1.5 to +1.5 (Tabachnick et al., 2007), the dataset was treated as normally distributed. Accordingly:

Table 1. Skewness and Kurtosis Values of SDL-TS and TPACS

Data Collection Tools	Skewness	Kurtosis
Technological Pedagogical Content Knowledge (TPACK) Self-Efficacy Scale	,424	1,009
Self-Directed Learning with Technology Scale (SDL-TS)	-,523	,225

•One-way ANOVA analyses were performed to evaluate differences in SDL-T and TPACK scores based on grade level, GPA, technology use frequency, and technological predisposition. Post-hoc Scheffé tests were conducted whenever significant differences were identified. Descriptive statistics (mean, standard deviation, frequency) were also calculated to support the interpretation of findings.

Findings

In this section, the statistical analyses conducted on the scores obtained from the SDL-T and TPACK scales are presented. Since the data showed a normal distribution across all examined variables—grade level, GPA, frequency of technology use, and technological predisposition—parametric tests were applied. Specifically, one-way ANOVA procedures were used to determine whether the participants' mean scores differed significantly according to these variables. The relevant descriptive statistics and test results are summarized below.

Table 2. Descriptive Analysis Results of SDL-TS Scores Based on Grade Level

Grade Level	N	X̄	s
2nd Year	25	4,173	,178
3rd Year	30	4,288	,138
4th Year	24	4,445	,202

Table 2 presents the descriptive results for SDL-T scores based on grade level. The findings reveal a gradual increase in mean SDL-T scores from 2nd-year students to 4th-year students. However, to determine whether these observed differences were meaningful, a one-way ANOVA was conducted.

Table 3. ANOVA Results for (SDL-TS) Scores According to Grade Level

	Sum of Squares	df	Mean Square	F	p
Between Groups	,906	2	,453		
Within Groups	58,616	76	,771	,587	,558
Total	59,521	78			

ANOVA results (Table 3) show that although SDL-TS scores tended to rise as students progressed through their undergraduate program, the differences among grade levels did not reach statistical significance ($p > .05$). This indicates that grade level alone is not a determining factor in students' technology-supported self-directed learning skills.

Table 4. Descriptive Analysis Results of SDL-TS Scores by GPA Variable

GPA	N	X̄	s
2,00-2,59	15	4,211	,625
2,50-2,99	43	4,220	,961
3,00-3,50	21	4,523	,830

As shown in Table 4, students with higher GPA displayed slightly higher SDL-TS mean scores. Nevertheless, the ANOVA presented in Table 5 demonstrates that these differences were not statistically significant ($p > .05$). This suggests that academic achievement, as measured by GPA, does not create a meaningful distinction in pre-service teachers' SDL-TS levels.

Table 5. ANOVA Results for SDL-TS Scores According to GPA

	Sum of Squares	df	Mean Square	F	p
Between Groups	1,439	2	,720		
Within Groups	58,082	76	,764	,942	,394
Total	59,521	78			

Table 5 indicates that although differences were noted in SDL-T scores based on GPA, these disparities were not statistically significant. The descriptive analysis results for the variable of frequency of technology use are presented in Table 6.

Table 6 Descriptive Analysis Results for SDL-TS Scores by Frequency of Technology Use

Frequency of Technology Use	N	X̄	s
1	10	3,633	,288
2	29	4,086	,162
3	31	4,408	,118
4	9	5,351	,137

According to Table 6, a higher frequency of technology usage among pre-service science teachers corresponds to increased mean SDL-T scores. An ANOVA test was conducted to evaluate the statistical significance of these differences related to usage frequency. The results are presented in Table 7.

Table 7 ANOVA Results for SDL-TS Scores According to Frequency of Technology Use

	Sum of Squares	df	Mean Square	F	p
Between Groups	16,093	3	5,364		
Within Groups	43,428	75	,579	9,264	,000
Total	59,521	78			

Table 7 demonstrates that higher technology-use frequency is associated with substantially higher SDL-T scores, with post-hoc analyses confirming significant differences particularly between high-frequency and low-frequency users. This pattern highlights that the quality and consistency of students' digital engagement may play a decisive role in developing self-regulated digital learning skills. The relevant results are presented in Table 8.

Table 8 Post-Hoc Scheffé Analysis Results for SDL-TS Scores According to Frequency of Technology Use

Frequency of Technology Use (I)	Frequency of Technology Use (J)	Mean Difference (I-J)	Std. Error	p
1	2	-,452	,279	,456
	3	-,775	,276	,447
	4	-1,718*	,349	,000
2	1	,452	,279	,456
	3	-,322	,196	,447
	4	-1,265*	,290	,001
3	1	,775	,276	,057
	2	,322	,196	,447
	4	-,943*	,288	,018
4	1	1,718*	,349	,000
	2	1,265*	,290	,001
	3	,943*	,288	,018

Table 8 shows that SDL-T levels rise alongside the frequency of technology use. A statistically significant difference exists between pre-service teachers with high usage frequency and those with low usage frequency The descriptive analysis results for the variable of technology use predisposition are presented in Table 9.

Table 9. Descriptive Statistics of SDL-TS Scores According to Technology Use Predisposition

Technology Use Predisposition	N	$\bar{X}$	s
1	4	2,958	,519
2	28	3,886	,138
3	38	4,688	,110
4	9	4,537	,294

Table 9 demonstrates that as the predisposition of teacher candidates toward technology use strengthens their average SDL-T scores also increase. ANOVA test was applied to examine the statistical significance level of this difference in terms of technology use predisposition. The results are presented in Table 10

Table 10. ANOVA Results for SDL-TS Scores According to Technology Use Predisposition

	Sum of Squares	df	Mean Square	F	p
Between Groups	18,222	3	6,074	11,031	,000
Within Groups	41,299	75	,551		
Total	59,521	78			

When Table 10 is examined,, an increase in technology use predisposition among pre-service science teachers results in statistically significant differences in SDL-T scores. To further examine the significant differences between groups, Scheffé post-hoc analysis was conducted. The relevant results are presented in Table 11.

Table 11. Post-Hoc Scheffé Analysis Results for SDL-TS Scores According to Technology Use Predisposition

Technology Use Predisposition (I)	Technology Use Predisposition (J)	Mean Difference (I-J)	Std. Error	p
1	2	-,928	,396	,150
	3	-1,730*	,390	,001
	4	-1,578*	,445	,009
2	1	,928	,396	,150
	3	-,801*	,184	,001
	4	-,650	,284	,166
3	1	1,730*	,390	,001
	2	,801*	,184	,001
	4	,151	,275	,959
4	1	1,578*	,445	,009
	2	,650	,284	,166
	3	-,151	,275	,959

As shown in Table 11, SDL-T levels increase with higher technology use proficiency. The difference between pre-service science teachers with high and low technology use proficiency is statistically significant.

Table 12. Descriptive Analysis Results of Pre-Service Teachers' TPACK

Grade Level	N	X̄	s
2nd Year	25	3,7510	,0853
3rd Year	30	3,838	,0582
4th Year	24	4,915	,0797

Table 12 shows that the mean TPACK scores of pre-service science teachers increase alongside their grade level. To examine whether the differences between grade levels are statistically significant, an ANOVA test was conducted. The results are presented in Table 13

Table 13. ANOVA Results of TPACKS Scores by Grade Level Variable

	Sum of Squares	df	Mean Square	F	p
Between Groups	,544	2	,272		
Within Groups	10,838	76	,143	1,906	,156
Total	11,381	78			

Upon reviewing Table 13, it is evident that although there are differences in TPACK scores across class levels, these do not constitute a statistically significant difference. The descriptive analysis results of the GANO variable are presented in Table 14.

Table 14. Descriptive Analysis Results of TPACKS Scores by GPA Variable

GPA	N	X̄	s
2,00-2,59	15	3,860	,0978
2,50-2,99	43	3,836	,0584
3,00-3,50	21	3,954	,0845

Table 14 indicates that the average Technological Pedagogical Content Knowledge scores of the candidates rise as their general weighted grade point averages increase. ANOVA test was applied to examine the statistical significance level of this difference in terms of the increase in general weighted grade point averages. The results are presented in Table 15.

Table 15. ANOVA Results for TPACKS Scores According to GPA

	Sum of Squares	df	Mean Square	F	p
Between Groups	,202	2	,101		
Within Groups	11,180	76	,147	,685	,507
Total	11,381	78			

Table 15 demonstrates that while variations exist in TPACK scores regarding the GPA variable, these are not statistically significant. Descriptive analysis results regarding the variable of frequency of technology use are presented in Table 16.

Table 16. Descriptive Analysis Results for TPACKS Scores by Frequency of Technology Use

Frequency of Technology Use	N	X̄	s
1	10	3,607	,141
2	29	3,769	,057
3	31	3,912	,048
4	9	4,361	,141

Table 16 shows a correlation where increased frequency of technology use among pre-service science teachers leads to higher mean TPACK scores. In order to examine whether the difference in terms of frequency of technology use is statistically significant, an ANOVA test was conducted. The results are presented in Table 17

Table 17. ANOVA Results for TPACKS Scores According to Frequency of Technology Use

	Sum of Squares	df	Mean Square	F	p
Between Groups	3,210	3	1,070		
Within Groups	8,171	75	,109	9,823	,000
Total	11,381	78			

As seen in Table 17, the increase in technology usage frequency among candidates creates a statistically significant difference in their TPACK scores. In order to examine the details of the statistically significant difference between the groups, the Scheffé post-hoc analysis was conducted. The relevant results are presented in Table 18.

Table 18. Post-Hoc Scheffé Analysis Results for TPACKS Scores According to Frequency of Technology Use

Frequency of Technology Use (I)	Frequency of Technology Use (J)	Mean Difference (I-J)	Std. Error	P
1	2	-,161	,121	,621
	3	-,304	,129	,101
	4	-,753*	,151	,003

2	1	,161	,121	,621
	3	-,143	,085	,426
	4	-,592*	,125	,000
3	1	,304	,120	,101
	2	,143	,085	,426
	4	-,449*	,124	,007
4	1	,753*	,151	,000
	2	,592*	,125	,000
	3	,449*	,124	,007

Table 18 confirms that TPACK levels rise as the frequency of technology use increases. There is a statistically significant difference between teachers with high versus low frequency of technology use. Descriptive analysis results regarding the variable of technology use predisposition are presented in Table 19.

Table 19. Descriptive Statistics of TPACKS Scores According to Technology Use Predisposition

Technology Use Predisposition	N	$\bar{X}$	s
1	4	3,306	,519
2	28	3,748	,138
3	38	3,957	,110
4	9	4,147	,294

Table 19 illustrates that as the tendency of pre-service science teachers to use technology grows, their mean TPACK scores also increase. In order to examine whether the difference in terms of technology use predisposition is statistically significant, an ANOVA test was conducted. The results are presented in Table 20

Table 20. ANOVA Results for TPACKS Scores According to Technology Use Predisposition

	Sum of Squares	df	Mean Square	F	p
Between Groups	2,671	3	,890		
Within Groups	8,710	75	,116	7,668	,000
Total	11,381	0,89			

Table 20 indicates that an increased tendency toward technology use among pre-service science teachers results in a statistically significant difference in TPACK scores. In order to examine the details of the statistically significant difference between the groups, the Scheffé post-hoc analysis was conducted. The relevant results are presented in Table 21.

Table 21 Post-Hoc Scheffé Analysis Results for TPACKS Scores According to Technology Use Predisposition

Technology Use Predisposition (I)	Technology Use Predisposition (J)	Mean Difference (I-J)	Std. Error	p
1	2	-,441	,182	,127
	3	-,651*	,179	,007
	4	-,840*	,204	,002
2	1	,441	,182	,127
	3	-,209	,084	,116
	4	-,399*	,130	,031
3	1	,651*	,179	,007
	2	,209	,084	,116
	4	-,189	,126	,031
4	1	,840*	,204	,002
	2	,399*	,130	,031
	3	,189	,126	,527

According to Table 21, TPACK levels improve as the technological tendency increases. The difference between candidates with a strong tendency to use technology and those with a weak tendency is statistically significant.

Discussion and conclusion

This research aimed to investigate the Self-Directed Learning with Technology (SDL-T) skills and TPACK levels of pre-service science teachers in relation to various variables. The findings indicated no statistically significant disparities in SDL-TS and TPACK scores regarding class level or Grade Point Average (GPA). While mean scores for both scales generally rose with higher class levels and GPAs, these increases were not statistically significant across the groups. These results suggest that the absence of significant differences across grade level and GPA may be attributed to the inherently multidimensional nature of SDL-T, which is shaped less by formal academic progression and more by individual factors such as motivation, prior digital experiences, and learning autonomy. These findings align with studies emphasizing that academic indicators do not reliably predict digital self-regulation in learning environments (Hasgören & Seçkin, 2023). Consequently, a multidisciplinary perspective is essential for comprehending and improving self-directed learning processes

Considering these findings, the lack of significant differences in technology-supported self-directed learning with technology learning across demographic variables such as class level and GPA may be explained by the multidimensional and highly individualized nature of self-directed learning with technology. Factors such as individual motivation, learning strategies, digital literacy, learning needs, and the quality of the learning environment appear to play a more decisive role than class level or academic achievement. Therefore, adopting a multidisciplinary approach is critical for understanding and enhancing self-directed learning processes.

The absence of a statistically significant relationship between academic achievement and technology-supported self-directed learning may stem from the complex and multifaceted structure of learning processes; the mediating role of variables such as motivation, attitudes, and willingness; the fact that technology and self-directed learning do not influence all learners to the same extent; and the influence of other factors such as socioeconomic status, instructional methods, and learning environments on academic achievement. Prior research also suggests that the effects of technology and SDL-T on academic performance are often indirect, multidimensional, and context-dependent, and therefore may not always yield statistically significant differences.

Although students with higher academic achievement demonstrated higher SDL-T skills, the differences between groups were not significant. While some studies report a strong and positive relationship between academic success and technology-use level (Geng et al., 2019), Li et al. (2025) emphasize that the relationship is positive but weak. Similarly, SDL-T skills increased as class levels rose among pre-service science teachers, yet no significant differences were observed. Karabulut Coşkun & Bayır (2025) likewise reported that technology-use levels increased with class level.

Other findings of the study indicated that pre-service science teachers' frequency of instructional technology use and their technological affinity resulted in significant differences in both SDL-T and TPACK scores. Higher levels of affinity and usage frequency corresponded to higher scores. Attitudes toward self-directed learning with technology learning are directly related to learners' interest in information and communication technologies (Sumuer, 2018). According to Bhattacharjee & Deb (2016), learners' ability to use these tools effectively is a critical factor in achieving learning goals.

However, not only usage frequency but also the quality of technology integration is essential. While this study found a positive impact of technology-use frequency on SDL-T and TPACK, Consoli et al. (2025) noted that low-quality integration may lead to negative outcomes. When supported with high-quality pedagogical practices, technology enhances students' behavioral engagement and digital skills (Vitanova et al., 2014), whereas excessive use or low-level integration may reduce learning efficiency. Supporting SDL-T is particularly crucial for individuals with advanced technological pedagogical competencies.

Overall, the findings aim to identify the key variables influencing pre-service science teachers' SDL-T and TPACK. While both skills tended to increase as students progressed through their university programs and as GPAs increased, these differences were not significant. Instead, frequency of instructional technology use and technological affinity emerged as key determinants. Students' interest in a subject or activity strengthens participation and learning (Egara & Mosimege, 2025). Sustained motivation and interest promote skill development, and learners tend to be more attentive and achieve deeper learning outcomes when they engage with topics of personal relevance (Harackiewicz et al., 2016; Renninger & Hidi, 2015). Thus, high-quality technology integration plays a crucial role in supporting digital skills and engagement (Consoli et al., 2025).

The absence of significant differences in TPACK and SDL-T across class levels and GPA aligns with both the structure of teacher education programs and the shared characteristics of teacher candidates. Since all candidates grow up exposed to digital technologies and complete similar instructional technology courses, substantial differences among them are unlikely. Studies by Balcı (2020) and Balçın & Ergün (2018) likewise show that TPACK perceptions do not significantly differ by class level or academic achievement; instead, factors such as access to technology and frequency of use are more influential.

Similarly, high academic achievement does not necessarily indicate high levels of SDL-T. Some high-achieving students rely more heavily on instructors, whereas those with moderate GPAs may demonstrate stronger digital self-learning habits. Research indicates that metacognitive awareness and motivation are more decisive in self-directed learning with than GPA (Hasgören & Seçkin, 2023). GPA does not directly reflect candidates' technology integration skills, as it primarily represents success in disciplinary and pedagogical coursework. TPACK, however, measures the integrated use of technological, pedagogical, and content knowledge—skills not automatically linked to academic performance. Balçın & Ergün (2018) similarly found that owning a computer, time spent using technology, and frequency of use were more influential predictors than GPA.

The lack of significant class-level differences in TPACK and SDL-T may be due to early exposure to instructional technologies in teacher education programs. Courses such as "Instructional Technologies and Material Design," typically offered in the first or second year, equip students with core TPACK components early in their undergraduate training. Studies by Balcı (2020) and Sancar Tokmak et al. (2013) also found no significant differences across grade levels. Many teacher candidates enter university with strong initial technology skills, consistent with Prensky's (2001) "digital natives" concept. Research further suggests that technology-use levels are already high among teacher candidates (Kırbağ Zengin & Kırılmazkaya, 2015). Limited technology integration during teaching practicum may also hinder TPACK development (Hall, 2006). In many practicum settings, student teachers encounter only basic computer use and receive limited guidance on integration.

Similar patterns appear in SDL-T: class-level differences may not emerge because personal motivation and technology access are more influential than demographic variables. Köse (2023) found no significant differences in self-directed learningacross demographic groups, while online learning experiences had stronger effects. Additionally, as TPACK and SDL-T measurements rely largely on self-report instruments, differences may be masked by students' self-perceptions. Lower-level students may overestimate their abilities, while upper-level students may evaluate themselves more critically.

The results of the present study demonstrate that the most decisive factors in the development of TPACK and SDL-T among pre-service science teachers are technology-use frequency and technological affinity. The success of the intended technology integration within teacher education programs is therefore closely tied to candidates' development of positive attitudes toward digital tools and self-regulation skills.

Implications and recommendations

The results indicate that strengthening TPACK and SDL-T among pre-service science teachers depends more on technological engagement than on academic indicators such as grade level or GPA. Teacher education programs should therefore prioritize hands-on digital creation tasks, scaffolded technology-integration activities, and opportunities for sustained self-directed learning with technology. This study is limited by its single-institution sample, which restricts generalizability. Additionally, cross-sectional design prevents conclusions about causal relationships. The reliance on self-report instruments may introduce perceptual bias, and subgroup sizes in ANOVA comparisons were uneven, potentially reducing statistical power. Future studies should employ longitudinal designs to track changes in TPACK and SDL-T over time, and mixed-methods approaches to capture how teacher candidates integrate technology in authentic classroom settings. Multi-institutional comparative studies may also reveal structural differences across teacher education programs that influence digital competency development.

Declarations

Informed consent

This study involved human participants; therefore, informed consent procedures were followed in accordance with ethical research standards. Before data collection, all pre-service science teachers were informed about the purpose, scope, voluntary nature, and confidentiality principles of the study. Participation was entirely voluntary, and no identifying personal information was collected. Informed consent was obtained verbally and in written form prior to administration of the data collection instruments. Since no photographs, audio–video records, or any identifying images of the participants were used, no additional consent was required for the publication of personal data.

Availability of data and materials

The datasets generated and analyzed during the current study consist of anonymized responses obtained from pre-service science teachers. Due to the confidential nature of the participant information and institutional restrictions, the raw data is not publicly available. However, de-identified data or summary statistics may be provided by the corresponding author upon reasonable request.

Competing interests

The author declares that there are no financial or non-financial competing interests associated with this study. No funding, sponsorship, or financial support was received from any individual or organization, and the author has no personal, academic, or institutional conflicts that could have influenced the conduct or reporting of this research.

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Authors' contributions

Author 1 contributed primarily to the research design, data collection, data analysis, and the drafting of the manuscript. Author 2 contributed to the literature review, interpretation of findings, and the revision of the final manuscript. Both authors approved the final version of the paper.

Artificial intelligence

Artificial intelligence tools were used only for language-related support during the preparation of this manuscript. Specifically, AI-assisted software was utilized to improve the clarity of expression, refine academic tone, and support English to Turkish translation during the editing process. No AI tool was used for generating research data, conducting analyses, interpreting results, or producing the scientific content of the study. All conceptual, methodological, analytical, and interpretive components of the research were carried out solely by the author.

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