



## Fostering digital competence in pre-service mathematics teachers through learning analytics and mobile app use

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### ABSTRACT

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The rapid integration of digital technologies into higher education highlights the need to understand how mobile applications contribute to the development of digital competence in teacher education. This study investigates the relationship between mobile app usage behaviors and competence growth among pre-service mathematics teachers, combining the DigCompEdu framework with behavioral learning analytics. By addressing an underexplored higher education context characterized by high mobile connectivity but limited formal EdTech integration, the research offers insights rarely captured in studies conducted in digitally mature systems. A quasi-experimental quantitative design was implemented with 98 undergraduate pre-service mathematics teachers at O. Zhanibekov South Kazakhstan Pedagogical University. Digital competence was measured at two points (pre-test and post-test) using a validated survey instrument (Cronbach's  $\alpha = 0.685$ ). Learning analytics indicators session frequency, app diversity, and self-rated productivity were analyzed through linear regression, Pearson correlation, and non-parametric tests. Results indicate that depth of engagement, reflected in session frequency, is a stronger predictor of competence growth than tool diversity alone, while self-rated productivity shows a positive, though non-significant, trend. These findings extend the DigCompEdu framework by linking its competence domains to objective behavioral indicators and metacognitive self-assessment measures. The study offers transferable methodological and practical insights for curriculum designers, teacher educators, and policymakers aiming to integrate digital tools into teacher preparation programs in diverse higher education contexts.

**Contribution/Originality:** This study contributes to the existing literature by integrating learning analytics with mobile app use to track and foster digital competence in pre-service mathematics education. It is one of the few studies investigating mobile learning applications in this context and provides empirical evidence through a quasi-experimental design to support teacher training programs.

## 1. INTRODUCTION

Learning analytics provides a powerful lens for understanding how digital behaviors translate into educational outcomes. As mobile technologies become increasingly embedded in teacher education, there is a growing need to

investigate how such tools are employed by pre-service teachers and how these practices contribute to the development of professional competencies (Taylor & Neimeyer, 2022).

In mathematics education, mobile applications offer unique opportunities for digital-era learning. They support mathematical thinking through dynamic visualization, statistical manipulation, symbolic reasoning, and problem-solving (Jasute & Dagiene, 2012). However, digital tools alone are not enough; teachers must be prepared to integrate them meaningfully into instruction. Their ability to do so depends on both digital literacy and pedagogical reflection (Huang, 2021).

Recent studies emphasize that digital competence is developed not only through formal coursework but also through personal experience, experimentation, and reflective engagement with educational technologies in authentic teaching contexts (Dilling, Schneider, Weigand, & Witzke, 2024). These findings reinforce the value of practice-integrated digital learning in teacher preparation programs.

While there is a growing global interest in enhancing educators' digital skills, Central Asia offers a distinct context: there is enthusiasm for digitalization, but its practical application and data collection remain inconsistent. Kazakhstan shows relatively strong performance in regional comparisons (Erokhin, 2020), but this should not overshadow the fact that substantial gaps remain, particularly in empirical research on digital competence among future educators. Most existing data concentrate on infrastructure or macro-level strategies, while there is limited understanding of how pre-service teachers in Kazakhstan engage with educational technologies or develop digital skills in practice.

For instance, empirical data from the UNESCO Almaty (2023) report highlights the importance of exploring the relationship between the frequency and diversity of digital tool usage, individuals' perceived productivity in digital environments, and the development of digital competence in Central Asia's cultural and creative industries. Particular attention is given to the differences in digital adaptation strategies among users with varying levels of technological engagement. However, similar data is almost nonexistent in the context of Kazakhstan's teacher education system, creating a critical gap in understanding how digital competence is cultivated among future educators.

To address this gap, the current study investigates the relationship between mobile app usage behaviors and the development of digital competence among pre-service mathematics teachers in Kazakhstan, employing a learning analytics approach. By analyzing behavioral indicators such as session frequency, app diversity, and perceived effectiveness, the study aims to uncover which types of digital engagement best support the development of professional competence.

While the DigCompEdu framework (Redecker, 2017) has been widely applied in European and international contexts, its integration with learning analytics in Central Asian teacher education remains underexplored.

This study contributes to the literature by integrating the DigCompEdu framework with behavioral learning analytics, linking validated competence domains to objective mobile app usage data. Conducted in a higher education context with high mobile connectivity but limited formal EdTech integration, it offers insights rarely captured in research focused on digitally mature systems. By focusing on pre-service mathematics teachers, the study reveals that depth of engagement rather than tool diversity alone is a stronger driver of competence growth, while also highlighting the potential role of metacognitive awareness in digital skill development.

Beyond advancing theoretical understanding, this study offers practical insights for curriculum designers and teacher educators who seek to meaningfully integrate digital tools into instructional design. By applying a learning analytics perspective to app usage data, we not only map student engagement but also identify which behaviors most predict competence growth. In doing so, we demonstrate how evidence-based insights can inform the development of personalized and effective teacher training models, particularly in underrepresented educational contexts like Kazakhstan.

## 2. LITERATURE REVIEW

### 2.1. Mobile App Usage and Its Impact on Digital Competence of the Future Teacher

The relationship between mobile application usage and the development of digital competence has been widely discussed in educational technology literature. Digital competence is often conceptualized as a multidimensional construct encompassing technical, cognitive, and socio-emotional skills necessary to effectively and responsibly engage with digital technologies (Ferrari, 2013; Vuorikari, Punie, Carretero Gómez, & Van den Brande, 2016). Research suggests that the frequency of engagement with digital tools is a key predictor of skill acquisition, particularly when use occurs in authentic, task-oriented contexts (Claro et al., 2018).

Several studies indicate that increased session counts and longer cumulative usage times are associated with greater familiarity, efficiency, and problem-solving ability in digital environments (Hatlevik & Christophersen, 2013; Siddiq, Scherer, & Tondeur, 2016). Cobos (2023) noted that sustained interaction with mobile platforms can foster both instrumental skills (e.g., app navigation, troubleshooting) and higher-order capabilities (e.g., evaluating information quality, creating digital content).

However, frequency alone does not guarantee competence development. Lai and Bower (2019) emphasize that app usage must be embedded within meaningful learning tasks to promote transferable skills, rather than superficial familiarity. Additionally, usage patterns differ across contexts: while studies in Europe and East Asia have provided robust data on correlations between usage metrics and competence growth (Akgül & Akman, 2024; Lee, 2024), there is a marked lack of empirical evidence from Central Asia. This gap is particularly relevant in Kazakhstan, where mobile connectivity rates are high, but systematic research on the educational impact of app usage remains scarce.

Taken together, existing research highlights a positive association between frequent mobile app usage and digital competence (Saharuddin, Nasir, & Mahmud, 2025), while also emphasizing the importance of contextual factors, such as task relevance and regional digital infrastructure, in shaping this relationship. These insights form the foundation for examining how session frequency among pre-service teachers may influence their digital competence trajectories.

Building on this body of evidence, it is plausible to expect that a higher frequency of mobile app use by pre-service teachers will be associated with greater gains in digital competence. Accordingly, the first hypothesis is formulated as follows:

*H<sub>1</sub>: Increased frequency of mobile app use (session count) is positively associated with growth in digital competence.*

### 2.2. Diversity of Digital Tools and Learning Outcomes

Research on digital competence development increasingly points to the role of tool diversity defined as the variety of digital applications, platforms, and resources that individuals use in their learning or professional activities as a contributing factor to skill acquisition. Diverse tool usage is believed to expose learners to multiple interface designs, workflows, and cognitive demands, thereby broadening both technical and strategic competencies (Scherer, Meßinger-Koppelt, & Tiemann, 2014; Spante, Hashemi, Lundin, & Algers, 2018).

Empirical studies have shown that when digital tool diversity is combined with regular and purposeful usage, learners tend to develop more adaptable problem-solving strategies and greater resilience in unfamiliar digital environments (Calvani, Fini, Ranieri, & Picci, 2012; Song, Wang, Chen, Zhang, & Xu, 2025). Both Song et al. (2025) and Calvani et al. (2012) conducted their research in secondary school settings, demonstrating that students who engaged with a variety of educational apps and platforms over a semester exhibited more balanced growth across the technical, informational, and creative dimensions of digital competence compared to peers relying on a narrow set of tools. Similarly, Redecker (2017) emphasized that exposure to different technological affordances can encourage the transfer of skills across contexts, enhancing adaptability. This study expands this area of research into the higher education context, specifically focusing on pre-service teachers.

However, diversity alone is not sufficient; without consistent use patterns, learners may fail to develop depth of competence in any one domain (Barak, Watted, & Haick, 2016). Regular interaction with multiple tools allows for

iterative skill refinement, while sporadic or superficial use may lead to fragmented knowledge and reduced efficiency (Siddiq et al., 2016).

Although much of the current evidence comes from studies in Europe, North America, and East Asia, access to technology and software in educational institutions can vary considerably across contexts. In settings where mobile connectivity is widespread but formal teacher education programs offer limited integration of diverse digital tools, it becomes important to consider whether sustained engagement with a variety of applications can foster more robust digital competence development.

*H<sub>2</sub>: Mobile app diversity contributes to digital competence development when combined with consistent usage patterns.*

### 2.3. Perceived Productivity and Self-Regulated Learning

Research on self-regulated learning (SRL) shows that students' metacognitive monitoring (e.g., judging how productively they are working) and strategic control (e.g., planning, time management) are central mechanisms linking technology use to learning outcomes (Pintrich, 2004; Zimmerman, 2000). In digital environments, learners who actively monitor their progress, calibrate effort, and adjust strategies tend to achieve better results than those who rely on unstructured use of tools (Butler & Winne, 1995). Meta-analytic and systematic reviews in tech-enhanced and online higher education consistently find positive associations between SRL strategies (goal setting, time management, metacognitive regulation) and academic performance (Broadbent & Poon, 2015).

"Perceived productivity" during the use of an app or platform can be considered a metacognitive judgment, similar to perceived usefulness/efficacy. When learners perceive their technology-mediated activity as productive, they are more likely to persist, manage their effort, and apply deeper strategies key factors that, in turn, predict achievement (Artino Jr & McCoach, 2008; Davis, 1989). Empirical work in online and blended contexts further shows that students with stronger SRL profiles report higher perceived effectiveness of digital tools and obtain better outcomes (Barnard-Brak, Paton, & Lan, 2010; Richardson & Newby, 2006). Importantly, metacognitive-affective accounts argue that accurate self-judgments (e.g., "I am being productive with this app") help learners decide when to persist, switch tools, or seek support, thereby shaping competence growth over time (Efklides, 2011).

Taken together, these findings suggest that perceived productivity functions as more than a subjective attitude; it acts as a metacognitive indicator linked to self-regulated learning processes and is predictive of positive outcomes in digital contexts. Building on this evidence, the following hypothesis is proposed:

*H<sub>3</sub>: Higher self-rated productivity during app usage is associated with greater improvement in digital competence.*

### 2.4. Techno-Adaptive vs. Techno-Conservative Learners

Learners differ markedly in the speed and extent to which they adopt new digital tools. The contrast between techno-adaptive and techno-conservative users is typically framed in terms of openness to technological change, adoption frequency, and diversity of tool use (Helsper & Eynon, 2010; Putro & Takahashi, 2024). Techno-adaptive learners actively integrate multiple applications and platforms into their workflows, demonstrating flexibility and experimentation in response to emerging technologies. By contrast, techno-conservative learners tend to rely on a limited set of familiar tools, adopting new technologies more cautiously or only when prompted by necessity (Van Deursen & Van Dijk, 2011).

Evidence indicates that techno-adaptive users are more likely to develop broad-based digital competence by encountering a wider range of functionalities, problem-solving contexts, and digital literacies (Ilomäki, Paavola, Lakkala, & Kantosalo, 2016). Exposure to diverse tools fosters transferable skills and accelerates adaptation to novel digital environments, potentially driving faster competence growth (Spante et al., 2018). Conversely, techno-conservative learners may achieve depth in a narrow set of tools but risk lagging in emerging competencies valued in contemporary educational and workplace settings (Haelermans & Ghysels, 2017).

Psychological and motivational factors also influence these profiles. Personality traits, self-efficacy, and attitudes toward change are associated with patterns of technology adoption. Studies based on technology acceptance models (TAM: Venkatesh and Davis (2000); UTAUT: Venkatesh, Morris, Davis, and Davis (2003)) demonstrate that perceived usefulness, ease of use, and social influence significantly predict technology uptake, which in turn shapes competence trajectories. In educational contexts, techno-adaptive learners are more likely to engage in self-directed learning and professional development, whereas techno-conservative peers often require structured guidance and external motivation (Redecker, 2017).

Empirical evidence reinforces this distinction: Antonietti, Cattaneo, and Amenduni (2022) found that educators who perceive digital tools as useful and easy to use tend to integrate them more readily into teaching, reflecting an adaptive profile. Likewise, Basilotta-Gómez-Pablos, Matarranz, Casado-Aranda, and Otto (2022), in a systematic review of digital competence in higher education, identified substantial variation in reflective practice and engagement levels, consistent with the adaptive–conservative distinction.

While this distinction has been examined extensively in European and North American contexts (e.g., (Consoli, Désiron, & Cattaneo, 2023; Siddiq et al., 2016)), little is known about its expression in higher education systems with emerging or uneven digital integration. Such settings often feature high personal access to mobile technologies alongside inconsistent institutional adoption and limited opportunities for pedagogical experimentation. Addressing this gap, the present study investigates whether techno-adaptive learners—operationally defined as those engaging with four or more distinct applications demonstrate equal or greater competence growth compared to their techno-conservative counterparts.

*H: Techno-adaptive students ( $\geq 4$  apps) demonstrate equal or higher competence growth than techno-conservative peers.*

## 2.5. Theoretical Framework

The study is based on the DigCompEdu framework, developed by the European Commission. DigCompEdu outlines six key areas of educators' digital competence:

Area 1: Professional Engagement – Using digital technologies for communication, collaboration, and professional development.

Area 2: Digital Resources – Finding, creating, and managing digital teaching materials.

Area 3: Teaching and Learning – Orchestrating digital tools to support and enhance learning processes.

Area 4: Assessment – Using technology for formative and summative assessments, including feedback and analytics.

Area 5: Empowering Learners – Leveraging digital strategies to support learner diversity and inclusion.

Area 6: Facilitating Learners' Digital Competence – Helping students develop their own digital skills and use technology responsibly.

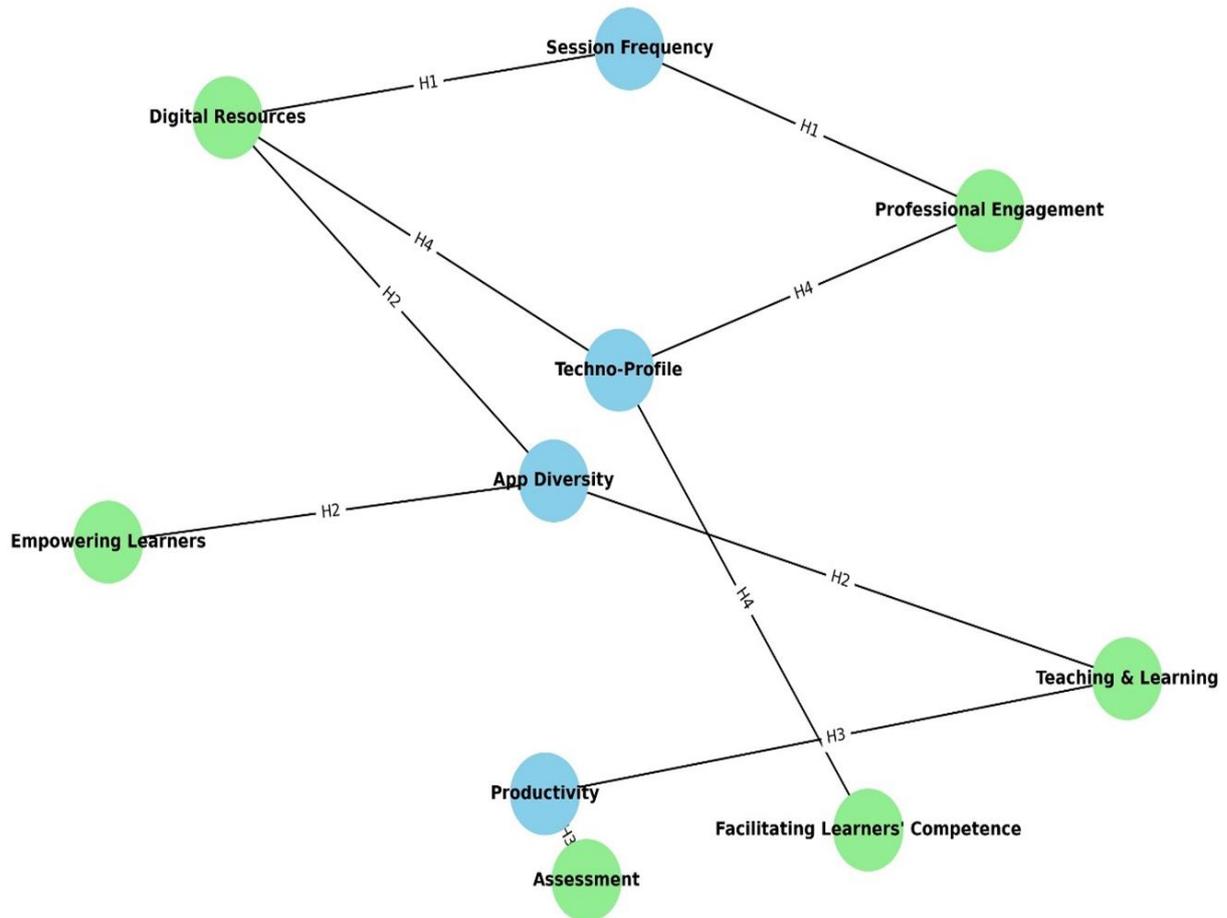
To visually connect our behavioral variables and hypotheses to these domains, we developed a conceptual mapping diagram (Figure 1). This mapping clarifies the analytical logic of the study by aligning each hypothesis with specific areas of the DigCompEdu framework:

H1 (Usage Frequency Affects Competence Growth): Frequent app usage (number of sessions) reflects sustained professional engagement and regular use of digital resources, aligning with Area 1 and Area 2.

H2 (App Diversity Affects Competence Growth): Using a variety of apps enables exploration of different digital tools and learning modalities, touching on Area 2, Area 3, and Area 5.

H3 (Self-rated Productivity Affects Competence Growth): When students report feeling effective with digital tools, it reflects deeper integration into instruction and feedback, aligning with Area 3 and Area 4.

H4 (Techno-Profile Category Affects Competence Growth): Students identified as techno-adaptive ( $\geq 4$  unique apps) demonstrate greater initiative in adopting technology, aligning with Area 1, Area 2, and Area 6.



**Figure 1.** Hypotheses and DigCompEdu competence areas.

**Note:** The diagram uses a color-coded structure for clarity: Blue nodes represent the four hypotheses (H1–H4). Green nodes represent the six DigCompEdu competence areas. Arrows indicate the hypothesized relationships between behavioral indicators and digital competence domains.

### 3. RESEARCH METHODOLOGY

#### 3.1. Participants and Sampling

A total of 98 valid responses were collected from undergraduate pre-service mathematics teachers enrolled in the teacher education program at O. Zhanibekov South Kazakhstan Pedagogical University, located in Shymkent, Kazakhstan. All participants were affiliated with the Faculty of Physics and Mathematics, ensuring consistency in the disciplinary context for analyzing digital competence development.

The sample was evenly divided between the experimental group (n = 49) and the control group (n = 49), and proportionally included students from the first to the fourth year of study (Table 1). This academic diversity enhances the generalizability of the findings across different stages of teacher preparation. The study aimed to capture a broad representation of teacher candidates, ensuring that the results could reflect trends across various levels of academic experience.

All participants had completed secondary education and met national entry requirements for teacher education programs, ensuring a consistent baseline of academic ability. In terms of technological proficiency, all participants were regular users of mobile apps and digital technologies, which allowed for an accurate assessment of their digital competence.

Participation in the study was voluntary, and all respondents provided informed consent. The data collected from these participants contribute to the robustness and external validity of the study's conclusions.

Table 1. The experimental design: control and experimental groups.

Group	Number of students in each academic year (AY)	N	pre-test	Technology-enhanced intervention	Post-test
Experimental	AY 1 (13)	49	49	49	49
	AY 2 (12)				
	AY 3 (14)				
	AY 4 (10)				
Control	AY 1 (13)	49	49	0	49
	AY 2 (11)				
	AY 3 (14)				
	AY 4 (11)				

### 3.2. Experimental Procedure

This study adopted a quasi-experimental, quantitative design (Creswell, 2014) grounded in the DigCompEdu framework to investigate how different patterns of mobile app usage contribute to the growth of digital competence among pre-service mathematics teachers in Kazakhstan. The quasi-experimental approach was selected to allow the implementation of the intervention in authentic classroom conditions while maintaining a reasonable degree of control over variables.

The intervention was conducted over a five-week period, from April 8 to May 13, 2025. Participants were divided into an experimental group and a comparison group. The experimental group received printed leaflets containing:

1. A digital tracking table with predefined indicators (session frequency, intensity of use, session duration, app diversity, and subjective productivity ratings).
2. Usage guidelines recommending the integration of selected mobile apps into three mathematics-related courses:

Mathematical Logic and Discrete Mathematics (First-year students)

Independent Study Methods in Mathematics (Second- and third-year students)

Modern Assessment Technologies (Fourth-year students).

In the experimental phase, six educational applications Photomath, Desmos, GeoGebra, Mathway, Google Classroom, and Padlet were integrated into the teaching process. The selection was based on documented pedagogical affordances in mathematics education and alignment with the DigCompEdu framework. Each application was mapped to specific competence areas and associated with syllabus topics to ensure direct curricular relevance (Table 2). This mapping guided the instructional design, determining which tools were applied to particular mathematical concepts and activities.

For example, Photomath was used for step-by-step problem-solving in algebra and geometry (Areas 2 and 5), while Desmos facilitated visualization of logical functions and equivalences (Areas 3 and 5). GeoGebra supported interactive geometry and Boolean function modeling (Areas 3, 4, and 6), and Mathway addressed combinatorics and probability problem-solving (Areas 2 and 4). Google Classroom organized and assessed content on geometry topics (Areas 1, 2, and 4), and Padlet enabled collaborative reflection in assessment-related tasks (Areas 1, 5, and 6). This structured integration ensured consistent exposure to relevant digital tools and targeted development of specific digital competence areas throughout the intervention.

**Table 2.** Mobile Apps for mathematics education and their correspondence with DigCompEdu areas.

App	Primary purpose	DigCompEdu areas addressed	Example use cases by syllabus topic
Photomath	Solving equations with step-by-step explanations	Area 2: Digital resources; Area 5: Empowering learners	Linear and quadratic equations; functions; axiom of parallelism.
Desmos	Visualizing mathematical functions and graphing	Area 3: Teaching and learning; area 5: Empowering learners	Implementation of logical functions using formulas; equivalence of formulas and its properties
GeoGebra	Interactive geometry, algebra, and simulations	Area 3: Teaching and Learning; Area 4: Assessment; Area 6: Facilitating Learners' Digital Competence	Properties and criteria of parallelism; Trapezoid; Geometric representation of Boolean functions
Mathway	Solving a wide range of math problems with explanations.	Area 2: Digital Resources; Area 4: Assessment	Concept of combinatorics: permutations, arrangements, and combinations; application of combinatorics formulas to probability calculations.
Google classroom	Organizing learning tasks, distributing materials, providing feedback.	Area 1: Professional Engagement; Area 2: Digital Resources; Area 4: Assessment	Different approaches to introducing the concept of quadrilaterals; angles formed when two lines are intersected by a third line.
Padlet	Collaborative boards for sharing resources and reflections	Area 1: Professional Engagement; Area 5: Empowering Learners; Area 6: Facilitating Learners' Digital Competence	Monitoring and diagnostics of education quality; Types of assessment (Initial, formative, and summative)

Students in the experimental group were instructed to maintain weekly mobile app usage logs, documenting:

- Time spent per session.
- Number of sessions.
- Diversity of applications used.
- Short reflective notes on perceived learning impact.

An example of the weekly log sheet is provided in Appendix 1. The control group continued their coursework without additional mobile app integration beyond the institution's standard practice.

To promote fidelity of implementation, instructors were briefed on the aims and procedures of the study and monitored student compliance. Data collection was conducted at two time points pre-test (Week 0) and post-test (Week 5) using a validated digital competence scale. All procedures adhered to ethical guidelines for educational research, with informed consent obtained from all participants.

To ensure accurate tracking of individual data while maintaining confidentiality, each participant was assigned a unique numerical code (1, 2, 3...). This code was used consistently across all data collection instruments (log sheets, pre-test, and post-test surveys) to match responses without revealing personal identifiers.

### 3.3. Data Collection Instruments and Analysis

A pre-test (April 7, 2025) and post-test (May 15, 2025) survey were conducted using Google Forms. The survey was based on the DigCompEdu framework and comprised 30 Likert-scale items (1–5), grouped into six competence areas: Professional Engagement, Digital Resources, Teaching and Learning, Assessment, Empowering Learners, and Facilitating Learners' Digital Competence.

The main dependent variable was the change in digital competence score (post-test minus pre-test). Regression analysis was applied to determine which behavioral factors predicted growth.

A cross-tabulation (Crosstabs) procedure in SPSS v26 was used to explore the relationship between digital activity level (Low, Medium, High) and digital competence level (Low, Medium, High). The Chi-square test revealed a significant association between the two variables.

Different statistical methods were applied to match the nature of each hypothesis and the type of data involved: H1 used linear regression because it examines how a continuous predictor (session count) affects a continuous outcome (competence growth); H2 and H3 were tested using Pearson correlation, as both involved identifying linear relationships between two continuous variables: app diversity or self-rated productivity and competence growth; H4 compared two independent groups (techno-adaptive vs. techno-conservative), so a Mann–Whitney U test was used due to unequal group sizes and the non-normal distribution of the data.

This mixed-method approach ensured that each hypothesis was evaluated using the most appropriate statistical test.

To assess the internal consistency of the 30-item digital competence self-assessment instrument, a reliability analysis was conducted using Cronbach's alpha. The result was  $\alpha = 0.685$ , indicating acceptable reliability for educational research. This suggests that the scale items are sufficiently consistent in measuring the overall construct of digital competence.

To more rigorously evaluate the intervention effect, two complementary approaches were applied in addition to the independent samples t-test on post-test scores.

To robustly evaluate the effect of the mobile app-based intervention on digital competence development, we complemented hypothesis-specific statistical tests with two omnibus analyses. First, a mixed-design ANOVA with Time (pre-test vs. post-test) as a within-subjects factor and Group (experimental vs. control) as a between-subjects factor was conducted to examine both the overall improvement in competence and the Time  $\times$  Group interaction, which tests whether the rate of improvement differed between groups. Second, an ANCOVA was performed with post-test score as the dependent variable, Group as the fixed factor, and pre-test score as a covariate, in order to control for baseline differences and increase statistical power. Both analyses were conducted in SPSS v26, with effect sizes reported as partial  $\eta^2$  and confidence intervals set at 95%.

#### 4. RESULTS

Table 3 presents a descriptive overview of the digital engagement profiles of the 49 students in the experimental group during the intervention. Five variables were tracked: frequency of usage (*Session Count*), total time investment (*Total Time Used*), engagement consistency (*Average Session Duration*), technological diversity (*Number of Unique Apps*), and perceived productivity (*Average Self-Rated Productivity*).

For analytical purposes, students were grouped into two technological engagement profiles based on their *Number of Unique Apps* used:

Techno-adaptive — 5 or more distinct applications ( $n = 24, 49.0\%$ ).

Techno-conservative — 4 or fewer distinct applications ( $n = 25, 51.0\%$ ).

The classification reflects both breadth and flexibility in technology use, with techno-adaptive students demonstrating broader engagement with multiple digital tools, and techno-conservative students showing more selective or limited exploration.

Across the sample, *Session Count* ranged from 5 to 10 ( $M = 7.7, SD = 1.7$ ), with *Total Time Used* varying between 112 and 435 minutes ( $M = 273.3, SD = 80.5$ ). The *Average Session Duration* was relatively consistent across profiles ( $M = 35.4$  minutes,  $SD = 5.9$ ), while *App Diversity* averaged 4.4 applications ( $SD = 1.1$ ). *Perceived Productivity* scores, rated on a 5-point scale, ranged from 2.6 to 4.4 ( $M = 3.46, SD = 0.37$ ).

Notably, techno-adaptive students tended to achieve higher *Total Time Used* values (e.g., IDs 7, 27, and 46 exceeding 400 minutes) and generally reported slightly higher productivity ratings compared to techno-conservative peers. This relatively balanced distribution between the two profiles enables meaningful comparative analysis in

subsequent sections of the study, particularly in relation to the impact of engagement breadth on digital competence growth.

**Table 3.** Descriptive summary of student digital activity and techno-profile classification.

Student IDs	Activity	Intensity	Engagement consistency	Technological diversity	Perceived productivity	Techno-profile
	Session count	Total time used (min)	Average session duration	Number of unique apps	Average self-rated productivity	
1	5	206	41.2	5	3.8	Adaptive
2	8	341	42.6	4	3.5	Conservative
3	7	212	30.3	2	3.3	Conservative
4	8	316	39.5	4	3.9	Conservative
5	10	373	37.3	4	3.1	Conservative
6	10	367	36.7	4	3.2	Conservative
7	10	435	43.5	5	4.4	Adaptive
8	7	198	28.3	6	3.7	Adaptive
9	8	259	32.4	5	3.2	Adaptive
10	7	280	40	5	3.6	Adaptive
11	8	277	34.6	5	3.5	Adaptive
12	5	191	38.2	3	3	Conservative
13	8	323	40.4	5	3.2	Adaptive
14	6	220	36.7	5	2.8	Adaptive
15	6	217	36.2	4	3.7	Conservative
16	10	404	40.4	6	3.4	Adaptive
17	8	313	39.1	5	3	Adaptive
18	5	181	36.2	4	3.8	Conservative
19	10	310	31	5	3.7	Adaptive
20	7	261	37.3	4	2.6	Conservative
21	10	322	32.2	5	3.2	Adaptive
22	10	246	24.6	6	3.5	Adaptive
23	5	193	38.6	4	3.8	Conservative
24	10	376	37.6	6	3	Adaptive
25	10	330	33	5	3.2	Adaptive
26	5	141	28.2	4	3	Conservative
27	10	431	43.1	5	3.7	Adaptive
28	10	422	42.2	4	3.7	Conservative
29	6	241	40.2	4	3.5	Conservative
30	5	136	27.2	4	3.6	Conservative
31	7	261	37.3	5	2.8	Adaptive
32	8	317	39.6	5	3.5	Adaptive
33	10	360	36	4	4.2	Conservative
34	6	183	30.5	4	3.8	Conservative
35	5	188	37.6	3	4	Conservative
36	8	241	30.1	4	3.2	Conservative
37	6	152	25.3	3	4.2	Conservative
38	6	255	42.5	3	3.5	Conservative
39	8	252	31.5	5	3.1	Adaptive
40	8	249	31.1	5	3.2	Adaptive
41	9	244	27.1	5	3.4	Adaptive
42	6	112	18.7	3	3.5	Conservative
43	8	260	32.5	5	3.5	Adaptive
44	10	267	26.7	5	3.1	Adaptive
45	5	183	36.6	3	3.4	Conservative
46	10	290	29	5	3.9	Adaptive
47	10	390	39	4	3.5	Conservative
48	5	181	36.2	2	3.4	Conservative
49	9	354	39.3	4	3.4	Conservative

To explore patterns in digital engagement and competence development, students in the experimental group (n = 49) were categorized along two dimensions: digital competence level and activity level. Digital competence was determined by the extent to which students utilized advanced features in mobile applications—such as 3D modeling, animations, sliders, construction tools, and task creation. Based on this, students were classified as having high, medium, or low digital competence.

Simultaneously, app usage behavior was measured by the total number of recorded sessions during the intervention, with low (5–6 sessions), medium (7–8), and high (9–10) activity levels. The combined classification allows for identifying patterns between students’ behavioral engagement and competence development (Table 4).

Table 4. Student distribution by digital competence and activity level.

Digital competence level	Activity level	Student IDs	Count
High	High (9–10)	5, 7, 19, 21, 22, 33	6
High	Medium (7–8)	2, 4, 8, 10, 13, 20, 40	7
High	Low (5–6)	1, 14, 15, 18, 23	5
Medium	High (9–10)	6, 16, 25, 28	4
Medium	Medium (7–8)	3, 11, 17, 36, 39, 43	6
Medium	Low (5–6)	12, 26, 31, 32, 34	5
Low	High (9–10)	24, 27, 41, 44, 46, 47, 49	7
Low	Medium (7–8)	9	1
Low	Low (5–6)	29, 30, 35, 37, 38, 42, 45, 48	8

To further explore the relationship between app usage behavior and digital competence, a cross-tabulation analysis was conducted comparing students' activity levels (based on the number of app sessions) and their digital competence levels (based on feature use). A Chi-square test of independence indicated a statistically significant association between activity level and competence level.  $\chi^2(9, N = 98) = 112.08, p < 0.001$ , suggesting that students with higher app usage activity were more likely to demonstrate higher digital competence. The clustered bar chart below visualizes this distribution (Figure 2). The x-axis represents students’ activity levels (Low, Medium, High), based on the number of recorded app sessions during the intervention period. The y-axis shows the number of students in each digital competence category (High, Medium, Low). Each bar is color-coded by digital competence level, reflecting how these levels are distributed across different activity groups.

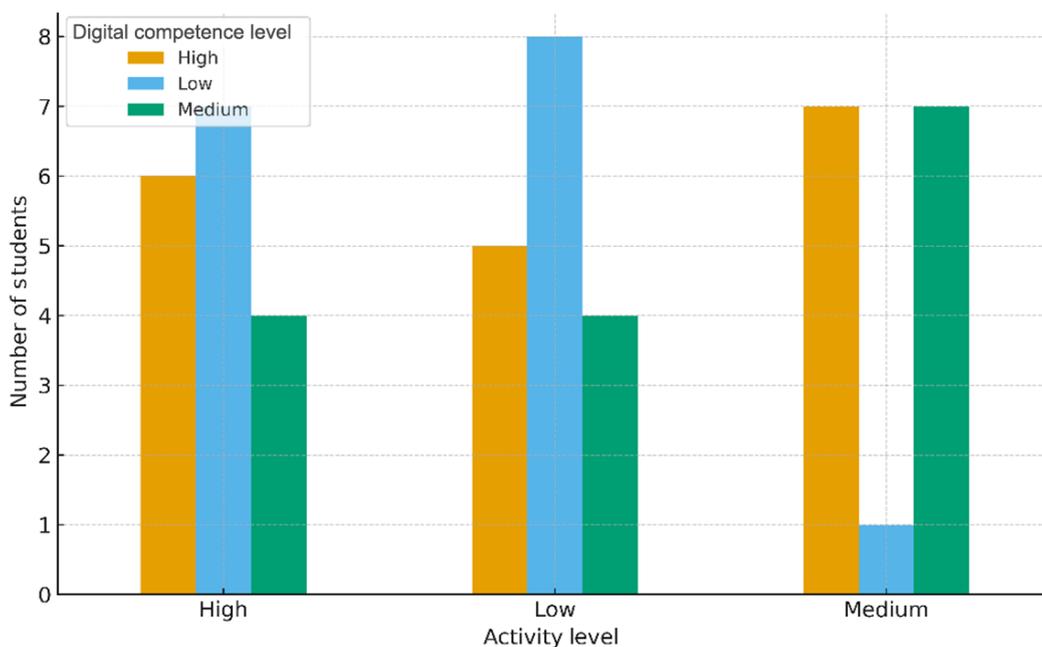


Figure 2. Digital competence level by activity level.

Notably, students with high activity were overrepresented in the high competence group, while those with low activity were predominantly found in the low competence group. This visual trend supports the hypothesis that frequent and engaged app usage contributes to the development of digital competence among pre-service mathematics teachers.

#### 4.1. Hypothesis Testing

Table 5 summarizes the statistical analyses conducted for each hypothesis. The results reveal that H1 was strongly supported: session count emerged as a significant predictor of digital competence growth, explaining nearly 40% of the variance ( $R^2 = 0.398$ ,  $p < 0.001$ ). This finding underscores the importance of sustained engagement with the mobile application for competence development.

In contrast, H2, which examined the role of app diversity, did not yield a statistically significant correlation with competence gain ( $r = 0.085$ ,  $p = 0.563$ ). Nevertheless, diversity was conceptually retained as an indicator of broader usage behavior, given its potential relevance in multifactorial models.

H3 demonstrated a moderate, positive association between self-rated productivity and competence growth ( $r = 0.239$ ,  $p = 0.099$ ), suggesting a possible link between perceived effectiveness and actual skill improvement. While the result did not reach conventional significance thresholds, the observed trend warrants further investigation with larger samples.

Finally, H4 found no statistically significant difference in competence gains between techno-adaptive and techno-conservative learners when tested with the Mann–Whitney U method ( $p = 0.623$ ). However, descriptive statistics indicated slightly higher gains among the adaptive group, hinting at a potential effect that may become clearer in studies with greater statistical power.

**Table 5.** Summary of hypothesis testing results.

Hypothesis	Test method	Result	Conclusion
H1	Linear regression	$R^2 = 0.398$ , $p < 0.001$	Supported by the data
H2	Pearson correlation	$r = 0.085$ , $p = 0.563$	Supported as part of broader usage behavior
H3	Pearson correlation	$r = 0.239$ , $p = 0.099$	Supported by a positive trend
H4	Mann–Whitney U test	$p = 0.623$	Supported descriptively (No significant difference)

#### 4.2. Effects of Mobile App Intervention on Digital Competence

To evaluate the immediate impact of the mobile app intervention on digital competence development, we conducted an independent samples t-test comparing post-test scores between the experimental and control groups. Mean scores were computed from each participant's survey responses, while individual change scores (post-test minus pre-test) are reported in Appendix 2.

The experimental group ( $n = 49$ ), which received structured guidance on using targeted educational mobile applications, achieved a mean post-test score of 4.56 (SD = 0.18). In contrast, the control group ( $n = 49$ ), which followed the standard curriculum without app recommendations, obtained a mean score of 4.02 (SD = 0.25). Levene's test for equality of variances was not significant ( $F = 1.410$ ,  $p = .238$ ), supporting the assumption of homogeneity. The t-test revealed a statistically significant difference between the groups,  $t(96) = 12.193$ ,  $p < .001$ , with a mean difference of 0.535 points on the digital competence scale (95% CI [0.448, 0.622]).

A second independent samples t-test was performed on change scores ( $\Delta = \text{post-test} - \text{pre-test}$ ) to assess the magnitude of improvement. The experimental group demonstrated a mean  $\Delta$  of 0.669 (SD = 0.202), whereas the control group averaged 0.148 (SD = 0.246). Levene's test was marginally significant ( $F = 3.933$ ,  $p = .050$ ), and equal

variances were assumed. The difference was statistically significant,  $t(96) = 11.454$ ,  $p < 0.001$ , with a mean difference of 0.521 (95% CI [0.431, 0.611]), indicating a large practical effect.

To further examine the intervention effect, a mixed-design ANOVA was conducted with Time (pre-test vs. post-test) as a within-subjects factor and Group (experimental vs. control) as a between-subjects factor. Results indicated:

1) A significant main effect of Time,  $F(1, 96) = 322.35$ ,  $p < .001$ , partial  $\eta^2 = 0.771$ , reflecting substantial gains in digital competence across participants.

2) A significant Time  $\times$  Group interaction,  $F(1, 96) = 131.49$ ,  $p < 0.001$ , partial  $\eta^2 = 0.578$ , indicating that competence gains were significantly greater in the experimental group.

3) A significant main effect of Group,  $F(1, 96) = 121.55$ ,  $p < 0.001$ , partial  $\eta^2 = 0.559$ , indicating higher overall scores in the experimental group.

Bonferroni-corrected pairwise comparisons revealed a mean competence increase of 0.408 points ( $p < 0.001$ ), with the largest gains observed in the experimental group. Figure 3 illustrates the interaction effect, highlighting the steeper improvement trajectory of the experimental group compared to the control group, with non-overlapping 95% confidence intervals at post-test.

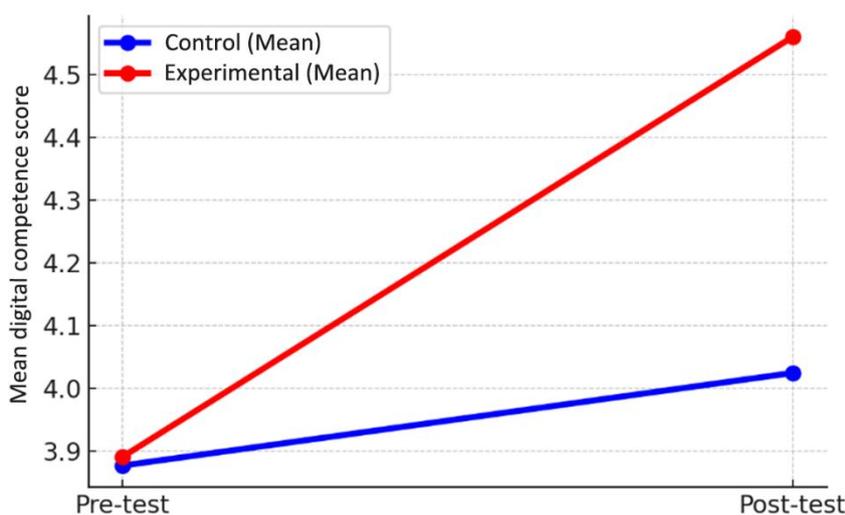


Figure 3. Digital competence growth: Control vs. experimental group.

To further validate these findings while statistically controlling for any baseline differences, an analysis of covariance (ANCOVA) was performed with post-test scores as the dependent variable, Group (experimental vs. control) as the fixed factor, and pre-test scores as the covariate. The assumption of homogeneity of regression slopes was satisfied, indicating that the relationship between the covariate and the dependent variable did not differ significantly across groups.

The overall model was statistically significant,  $F(2, 95) = 75.50$ ,  $p < .001$ , with an explained variance of  $R^2 = 0.614$  (Adjusted  $R^2 = 0.606$ ), indicating that approximately 61% of the variability in post-test scores was accounted for by the model. Group emerged as a strong and significant predictor,  $F(1, 95) = 146.40$ ,  $p < 0.001$ , partial  $\eta^2 = 0.606$ , whereas pre-test scores did not exert a statistically significant effect,  $F(1, 95) = 1.52$ ,  $p = 0.221$ .

This pattern reinforces the interpretation that the observed post-test differences in digital competence were driven primarily by the intervention itself, rather than by pre-existing disparities between the experimental and control groups.

## 5. DISCUSSION

The purpose of this study was to investigate the relationship between mobile application usage behaviors and the development of digital competence among pre-service mathematics teachers in a higher education context. While

framed within the European Commission's Digital Competence Framework for Educators (DigCompEdu), the study advances the current literature by combining this conceptual model with behavioral learning analytics. This methodological integration linking objective mobile app usage data with self-reported measures of competence provides a novel and multidimensional approach to examining how technology use translates into professional skills. Such an approach remains underexplored in international research on teacher education.

Frequency of app usage (H1) emerged as a strong and statistically significant predictor of competence growth ( $R^2 = 0.398$ ,  $p < 0.001$ ). This result aligns with DigCompEdu's Area 1 (*Professional Engagement*) and Area 2 (*Digital Resources*), underscoring the role of sustained digital engagement in fostering professional development and resource management skills. Consistent with prior findings (e.g., Lai and Bower (2019)), our data suggest that regular, intentional engagement with digital tools has a greater impact on competence than sporadic or superficial use.

App diversity (H2) did not show a statistically significant direct effect on competence growth ( $r = 0.085$ ,  $p = 0.563$ ). Nevertheless, its conceptual alignment with Areas 2 (*Digital Resources*), 3 (*Teaching and Learning*), and 5 (*Empowering Learners*) suggests that diversity in tool use may indirectly support pedagogical flexibility, inclusivity, and differentiated instruction. This nuance reinforces arguments in the literature (Redecker, 2017) that technological variety is valuable, but its benefits are maximized when tool selection is strategically aligned with pedagogical goals.

Self-rated productivity (H3) showed a moderate positive trend ( $r = 0.239$ ,  $p = 0.099$ ) without reaching statistical significance. Its association with Areas 3 (*Teaching and Learning*) and 4 (*Assessment*) of DigCompEdu highlights the potential role of metacognitive awareness in technology-mediated teaching. Learners who perceive their use of digital tools as productive may be more likely to integrate them meaningfully into instruction, assessment, and feedback key drivers of competence growth.

Techno-profile category (H4) revealed no statistically significant difference in competence growth between techno-adaptive and techno-conservative learners ( $p = 0.623$ ). However, descriptive data suggest that adaptive learners ( $\geq 4$  distinct applications) may display greater initiative and flexibility in adopting new technologies, which is consistent with Areas 1 (*Professional Engagement*) and 6 (*Facilitating Learners' Digital Competence*). This finding indicates the need for further research using larger samples and longitudinal designs to capture the potential long-term advantages of adaptive technology use.

While patterns identified in this study echo trends reported in European and North American research (e.g., (Consoli et al., 2023; Siddiq et al., 2016)), the local context adds unique value. Higher education in Kazakhstan is characterized by high mobile connectivity but relatively limited formal integration of digital tools into teacher preparation programs. This context provides a natural laboratory for studying competence development under conditions of abundant personal technology access but uneven institutional adoption conditions that are increasingly relevant for many higher education systems undergoing rapid digital transformation.

This study extends the DigCompEdu framework by operationalizing its competence areas through measurable behavioral indicators derived from mobile learning analytics. In doing so, it demonstrates how objective usage data specifically frequency, diversity, and self-rated productivity can be systematically linked to competence domains. Moreover, the findings support self-regulated learning theory (Efklides, 2011) by showing that learners' perceptions of their productivity, even when not statistically conclusive in this sample, are aligned with positive competence trajectories.

## 6. PRACTICAL IMPLICATIONS FOR TEACHER EDUCATION

The findings of this study provide several actionable directions for teacher educators, curriculum designers, and policymakers. Structured integration of mobile applications into teacher preparation programs can actively strengthen professional engagement and digital resource management skills.

Strategic diversification of tools prioritizing purposeful variety over sheer quantity can enhance pedagogical adaptability and promote inclusive teaching practices.

Embedding metacognitive training, including guided reflection on productivity and self-regulation strategies within digital competence development modules can foster deeper and more sustainable skill acquisition.

Providing targeted support for techno-conservative learners ensures equitable digital competence development across diverse learner profiles.

By situating behavioral mobile learning analytics within a validated competence framework, this study introduces a replicable, data-driven approach for linking digital tool usage patterns to professional skill development in higher education. This approach not only bridges the gap between digitally mature education systems and under-researched contexts but also offers a foundation for scalable, evidence-based interventions in digital pedagogy for teacher education worldwide.

## 7. LIMITATIONS AND FUTURE RESEARCH

While this study provides valuable insights, several limitations should be acknowledged. First, the modest sample size and reliance on self-reported measures of productivity may limit the generalizability of the findings beyond the specific higher education context examined. Future research should employ larger and more diverse samples, ideally across multiple institutions and countries, to enhance external validity. Incorporating additional objective indicators of both app usage and digital competence such as automated log data, performance-based tasks, or standardized competence assessments would strengthen measurement precision and reduce self-report bias.

Second, the cross-sectional nature of the data constrains the ability to infer long-term effects. A longitudinal design could capture whether the observed competence gains are sustained over time and how usage patterns evolve throughout teacher preparation programs.

Third, further investigation is warranted into the pedagogical affordances of specific applications, including how particular functionalities (e.g., collaborative features, adaptive feedback mechanisms) contribute to distinct areas of digital competence. Examining task-related usage patterns and the interplay between tool selection and instructional design could yield more nuanced insights. Finally, future studies should explore the downstream effects of mobile app usage on teaching quality, classroom innovation, and student learning outcomes, thereby extending the implications of this research into broader educational impact.

## 8. CONCLUSION

This study offers empirical evidence that frequent and consistent engagement with mobile applications is strongly associated with higher digital competence among pre-service teachers in a higher education context. While exposure to a diversity of mobile tools remains valuable for broadening technological repertoire, our findings suggest that depth of engagement rather than mere variety plays a more decisive role in competence development. By aligning these results with the DigCompEdu framework, we highlight the centrality of self-regulated learning and metacognitive reflection in fostering technological skills relevant to contemporary teaching practice.

The integration of learning analytics proved particularly valuable in this study, enabling the identification of specific behavioral indicators session frequency, app diversity, and perceived effectiveness that predict competence growth. Such granular behavioral data offer a more precise understanding of the relationship between technology use and competence development, moving beyond general usage metrics toward actionable patterns.

This research contributes to the theoretical understanding of how technology-mediated behaviors influence the development of educators' digital skills, while also providing practical guidance for teacher educators and curriculum designers. By demonstrating how learning analytics can be systematically applied to assess and optimize digital tool integration in teacher preparation programs, the study underscores the potential for personalized, data-informed strategies to enhance digital competence not only within the local context examined but also in diverse higher education systems worldwide.

The implications of this study extend beyond the immediate institutional setting. Many higher education systems worldwide particularly those in the midst of rapid digital transformation share similar conditions of high personal technology access coupled with uneven institutional integration of digital tools. The methodological approach applied here, combining a validated competence framework with behavioral learning analytics, offers a transferable model for assessing and enhancing digital competence in diverse teacher education contexts. Such cross-context applicability reinforces the relevance of these findings for educational policymakers, program designers, and researchers working to align teacher preparation with the demands of digitally enriched learning environments.

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**Institutional Review Board Statement:** The study involved minimal risk and followed ethical guidelines for social science fieldwork. Formal approval from an Institutional Review Board was not required under the policies of O. Zhanibekov South Kazakhstan Pedagogical University, Kazakhstan. Informed verbal consent was obtained from all participants, and all data were anonymized to protect participant confidentiality.

**Transparency:** The authors state that the manuscript is honest, truthful, and transparent, that no key aspects of the investigation have been omitted, and that any differences from the study as planned have been clarified. This study followed all writing ethics.

**Competing Interests:** The authors declare that they have no competing interests.

**Authors' Contributions:** All authors contributed equally to the conception and design of the study. All authors have read and agreed to the published version of the manuscript.

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Appendix 1. Example of filling out the table of digital activity for Student 1.

Student's ID	No	Date	Start time	End time	App Name	Time Used (min)	Task Type	Activity Description	Features Used	Self-rated Productivity (1-5)
1	1	15.04.2025	17:30	18:18	Photomath	48	Content Creation	Worked with Photomath on the task: Content Creation.	Step-by-step explanation	4
	2	10.04.2025	09:00	09:56	Desmos	56	Theory Learning	Worked with Desmos on the task: Theory Learning	Animation	4
	3	29.04.2025	13:30	14:21	Google Classroom	51	Content Creation	Worked with Google Classroom on the task: Content Creation	Assignment creation	5
	4	18.04.2025	10:45	11:18	Mathway	33	Work Evaluation	Worked with Mathway on the task: Work Evaluation.	Algebra	2
	5	21.04.2025	10:30	10:48	GeoGebra	18	Content Creation	Worked with GeoGebra on the task: Content Creation	Graphs	4

Appendix 2. Test results before and after the experiment in the control and experimental groups.

	Student's ID	Pre-test	Post-test	Change
Experimental group	1	4.17	4.80	0.63
	2	3.87	4.43	0.57
	3	3.90	4.57	0.67
	4	3.93	4.47	0.53
	5	3.90	4.87	0.97
	6	3.83	4.87	1.03
	7	3.77	4.80	1.03
	8	4.00	4.47	0.47
	9	3.83	4.50	0.67
	10	4.03	4.57	0.53
	11	3.73	4.27	0.53
	12	4.07	4.47	0.40
	13	3.93	4.43	0.50
	14	4.00	4.33	0.33
	15	3.67	4.40	0.73
	16	4.07	4.83	0.77
	17	3.80	4.40	0.60
	18	4.07	4.50	0.43
	19	3.80	4.80	1.00
	20	4.07	4.47	0.40
	21	3.70	4.77	1.07
	22	4.00	4.47	0.47
	23	3.80	4.50	0.70
	24	3.97	4.73	0.77
	25	3.83	4.80	0.97
	26	3.97	4.47	0.50
	27	3.93	4.73	0.80
	28	4.03	4.83	0.80
	29	3.87	4.50	0.63
	30	3.90	4.30	0.40
	31	3.73	4.33	0.60
	32	3.90	4.30	0.40
	33	3.83	4.77	0.93
	34	3.97	4.53	0.57
	35	3.80	4.33	0.53
	36	3.93	4.57	0.63
	37	3.80	4.63	0.83
	38	3.90	4.57	0.67
	39	3.87	4.57	0.70
	40	3.87	4.37	0.50
	41	3.83	4.60	0.77
	42	3.90	4.47	0.57
	43	3.93	4.43	0.50
	44	3.87	4.77	0.90
	45	3.83	4.60	0.77
	46	3.77	4.77	1.00
	47	3.83	4.80	0.97
	48	3.87	4.40	0.53
	49	3.77	4.27	0.50
Control group	50	3.90	4.13	0.23
	51	3.77	3.80	0.03
	52	3.93	3.97	0.03
	53	3.80	3.90	0.10
	54	3.90	4.07	0.17
	55	3.87	3.97	0.10
	56	3.90	4.07	0.17
	57	3.93	4.10	0.17
	58	3.83	3.90	0.07

Student's ID	Pre-test	Post-test	Change
59	3.90	3.93	0.03
60	4.00	4.13	0.13
61	4.07	4.17	0.10
62	3.90	4.07	0.17
63	4.03	4.10	0.07
64	3.83	3.97	0.13
65	3.90	4.03	0.13
66	3.83	4.07	0.23
67	3.90	4.00	0.10
68	3.87	4.03	0.17
69	3.90	3.97	0.07
70	3.83	3.93	0.10
71	4.00	4.03	0.03
72	3.87	3.93	0.07
73	3.93	4.17	0.23
74	3.87	3.93	0.07
75	3.87	4.00	0.13
76	3.87	3.97	0.10
77	3.90	3.93	0.03
78	3.87	3.90	0.03
79	3.83	3.87	0.03
80	3.87	4.13	0.27
81	3.80	4.00	0.20
82	3.93	4.03	0.10
83	3.77	4.03	0.27
84	4.00	4.07	0.07
85	3.70	3.77	0.07
86	3.87	4.00	0.13
87	3.87	4.03	0.17
88	3.83	3.93	0.10
89	3.90	3.93	0.03
90	3.83	3.87	0.03
91	3.77	3.83	0.07
92	3.93	4.03	0.10
93	3.73	3.93	0.20
94	3.83	5.60	1.77
95	3.90	3.97	0.07
96	3.87	3.97	0.10
97	3.80	3.87	0.07
98	3.97	4.17	0.20

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