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Effects of digital learning intervention on pre-service teachers' innovation competence: evidence from Kazakhstan

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ABSTRACT

Developing innovation competence (IC) is essential for pre-service teachers, as it enables them to effectively design, implement, and adapt instruction in increasingly complex and digitally enriched learning environments where technology integration, student-centered approaches, and pedagogical flexibility are critical. However, empirical evidence on how structured digital learning interventions (DLIs) foster multidimensional IC remains limited. This study examined the effect of a twelve-week structured DLI on IC in 156 third-year pre-service teachers using a quasi-experimental pretest–posttest design with a non-equivalent control group (CG). Participants completed the IC scale before and after the intervention. Results showed that the intervention significantly improved overall IC and all four dimensions: creative problem-solving (CPS), pedagogical adaptability, proactive initiative, and technology-enhanced instructional design, with the largest gains in CPS and technology-enhanced instructional design. Engagement with digital learning activities further predicted competence development, particularly in the intervention group. These findings suggest that integrating structured digital learning with intentional pedagogical design can effectively enhance innovation-oriented competencies. Teacher education programs can apply these insights to design interventions that prepare future educators for innovative, technology-rich classrooms.

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1. INTRODUCTION

The rapid digital transformation of education systems worldwide has substantially reshaped the professional profile and competency requirements of teachers [1]. Digital technologies, online learning environments, artificial intelligence tools, and data-driven instructional strategies are increasingly integrated into teaching practice [2]. This transformation reflects not only the adoption of technological tools but also broader systemic innovation in educational processes. Recent empirical studies and systematic reviews indicate that pre-service teachers' (PSTs') digital competence (DC) and technological pedagogical content knowledge (TPACK) are critical for effective teaching in digitally enriched learning environments [3]. For example, Hatlevik [4] demonstrated that higher levels of DC are associated with greater instructional effectiveness, while Li [5] found that TPACK significantly predicts readiness for technology-enhanced instruction.

However, effective participation in digitally transformed educational systems requires more than technological proficiency alone. Beyond DC, teachers are increasingly expected to demonstrate innovation competence (IC), which encompasses creativity, proactive initiative, pedagogical adaptability, and the ability to integrate new approaches into instructional practice [6], [7]. Structured digital learning interventions (DLIs) can support both technological and innovation-related capacities, enabling PSTs to develop multidimensional competencies required for contemporary teaching [8].

Despite the growing literature on DC and technology integration in teacher education, empirical attention to IC as a multidimensional construct remains limited [9], [10]. Most studies focus on digital literacy and technical skills, overlooking creativity, initiative, adaptability, and pedagogical innovation. Although digital transformation initiatives are widely implemented in teacher education, many programs continue to prioritize technical skill development rather than systematically fostering higher-order innovation-oriented competencies among pre-service teachers. Consequently, DC development is not consistently translated into sustained pedagogical innovation or adaptive instructional capacity.

In the present study, IC is conceptualized within the competence-based education framework and draws on innovation readiness models, integrating cognitive, motivational, and behavioral dimensions [11]–[13]. IC is operationalized as creative problem-solving (CPS), pedagogical adaptability, proactive initiative, and technology-enhanced instructional design. This framework allows for a comprehensive assessment of pre-service teachers' ability to apply innovative strategies in digitally enriched learning environments.

Another limitation in the existing literature concerns the geographical distribution of empirical evidence. There remains a scarcity of studies conducted in Central Asian contexts, where teacher education systems are undergoing rapid digital reform but remain underrepresented in international scholarship. Recent studies [14], [15] describe ongoing digital reforms in Kazakh and Central Asian teacher training systems; however, these studies primarily provide descriptive insights rather than statistically validated pretest–posttest evidence. Meta-analyses [16]–[22] indicate that teacher preparation programs integrating digital pedagogy can improve DC and related higher-order pedagogical skills. These findings suggest that digital learning environments may also foster innovation-related capacities. Nevertheless, IC as a distinct multidimensional construct has rarely been examined as a primary outcome variable in such syntheses. Given the conceptual overlap between DC and innovation-oriented pedagogical practices, these findings provide indirect support for the relevance of examining IC development [23], [24].

Developing IC through structured DLIs is critical for contemporary education reform. This approach is consistent with existing models of teacher DC and innovation-oriented pedagogy, which emphasize the integration of technological skills, pedagogical adaptability, and creative instructional design [25]. Teachers with higher IC are better equipped to implement innovative and adaptable instructional strategies, enhancing both teaching effectiveness and student learning outcomes. Accordingly, IC is conceptualized as a higher-order integrative construct rather than an extension of DC. By fostering proactive initiative, pedagogical adaptability, and technology-enhanced instructional skills, such interventions not only prepare pre-service teachers to meet the demands of digitally enriched classrooms but also support broader systemic goals of educational modernization and quality improvement. Empirical evidence also suggests that meaningful integration of digital tools into pedagogical training can serve as a catalyst for innovative instructional design rather than functioning merely as isolated technical additions [26]. However, the extent to which such systemic digital reforms translate into measurable improvements in IC among PSTs remains insufficiently documented across national contexts. This limitation is particularly evident in Kazakhstan, where ongoing educational modernization and digitalization policies have created strong institutional support for innovation-oriented teacher education, yet empirical evidence on how these reforms influence the development of PSTs' IC remains limited [27]–[32].

Given this context, Kazakhstan provides a relevant setting for examining how structured DLIs may contribute to the development of PSTs' IC. Therefore, the present study investigates the effect of a structured DLI on PSTs' IC in Kazakhstan using a quantitative pretest-posttest design. The primary aim is to determine whether participation in the DLI is associated with greater improvement in IC compared to regular instruction. Secondary objectives include examining differences in change across specific dimensions of IC and identifying digital engagement variables associated with IC development. By providing empirical evidence from a non-Western teacher education context, this study contributes to the broader international discussion on digital innovation in teacher preparation.

This study makes a novel contribution to the existing literature by conceptualizing IC as a multidimensional construct integrating cognitive, motivational, and behavioral components, thereby extending beyond the predominantly technology-centered focus of prior research. Building on this conceptualization, it advances the field by providing statistically validated evidence of the effects of a structured DLI on IC using a rigorous quantitative pretest-posttest design. Taken together, the study also contributes original empirical data from Kazakhstan, a Central Asian context that remains underrepresented in international research, while further enhancing understanding of how digital engagement variables shape the development of innovation-related competencies in pre-service teachers within digitally enriched learning environments. Therefore, the research questions (RQ) of the study are as: i) RQ1 examines whether participation in the DLI is associated with differences in IC improvement compared to regular instruction; ii) RQ2 identifies which IC dimensions demonstrate the greatest improvement in the intervention group; and iii) RQ3 assesses the extent to which digital engagement variables predict changes in IC and whether this relationship differs between the experimental group (EG) and the control group (CG).

2. METHOD

2.1. Research design

This study employed a quantitative quasi-experimental design with a non-equivalent CG and pretest–posttest measures [33]. Random assignment was not feasible due to institutional constraints; therefore, intact groups were used. A quasi-experimental design was chosen to accommodate administrative limitations while still allowing for comparison between intervention and CG over time. IC was treated as the dependent variable and measured at two time points: before the intervention (pretest, O1) and after the intervention (posttest, O2). Pretest scores were used to assess initial group comparability and were included as a covariate in subsequent analyses. The inclusion of a CG allowed for comparison of developmental changes between groups over time. The structure of the research design is presented in Table 1, where O1 and O2 represent pretest and posttest observations, respectively.

Table 1. Quasi-experimental non-equivalent CG design

Group	Pre-test	Intervention	Post-test
EG	O1: IC scale	Structured DLI	O2: IC scale
CG	O1: IC scale	Regular instruction	O2: IC scale

2.2. Participants

Participants were undergraduate PSTs enrolled in the 3rd year of the Primary Education (PE) program at Abai Kazakh National Pedagogical University (KazNU), Kazakhstan. Due to scheduling and administrative constraints, random assignment was not feasible; therefore, two intact groups were included in the study. The EG participated in the structured DLI, whereas the CG followed the standard curriculum. A total of 156 PSTs participated (78 per group). The mean age was 20.85 years (SD=1.25), ranging from 19 to 24 years. The majority of participants were female, reflecting the typical gender distribution in PE programs in Kazakhstan (EG: 66 female (F), 12 male (M); CG: 65 females, 13 male). Inclusion criteria: i) official enrollment in the 3rd year of the PE program; ii) provision of informed consent; iii) basic DL, defined as familiarity with standard productivity software and online learning platforms; and iv) availability to attend scheduled sessions during the intervention period. Exclusion criteria: i) prior professional teaching experience exceeding six months; ii) failure to provide informed consent; and iii) attendance below 80% of scheduled sessions. Pretest measurements were conducted to assess baseline equivalence between groups. Baseline equivalence was examined using independent samples t-tests for continuous variables (pretest IC scores and grade point average (GPA) and chi-square tests for categorical variables (gender and digital literacy levels). The analyses indicated no statistically significant differences between the experimental and CGs at baseline (p>0.05), suggesting that the groups were comparable prior to the intervention. Demographic and academic characteristics are presented in Table 2.

Table 2. Characteristics of participants

Group	n	Age (Mean±SD)	Gender (F/M)	GPA (Mean±SD)	DL level (B/I/A)	Prior training (yes/no)
EG	78	20.8±1.2	66/12	3.5±0.4	15/50/13	20/58
CG	78	20.9±1.3	65/13	3.6±0.5	16/48/14	22/56
Total	156	20.85±1.25	131/25	3.55±0.45	31/98/27	42/114

Note: B=Basic, I=Intermediate, A=Advanced. Prior training refers to previous participation in pedagogical or digital training programs. GPA is reported on a 4-point scale

2.3. Procedure

The study was conducted from September to December 2024 at the Department of Primary Education, KazNU, Kazakhstan. Figure 1 illustrates the structure and procedure of the DLI implemented in the present study. The intervention followed a structured sequence of pedagogical phases supported by digital engagement.

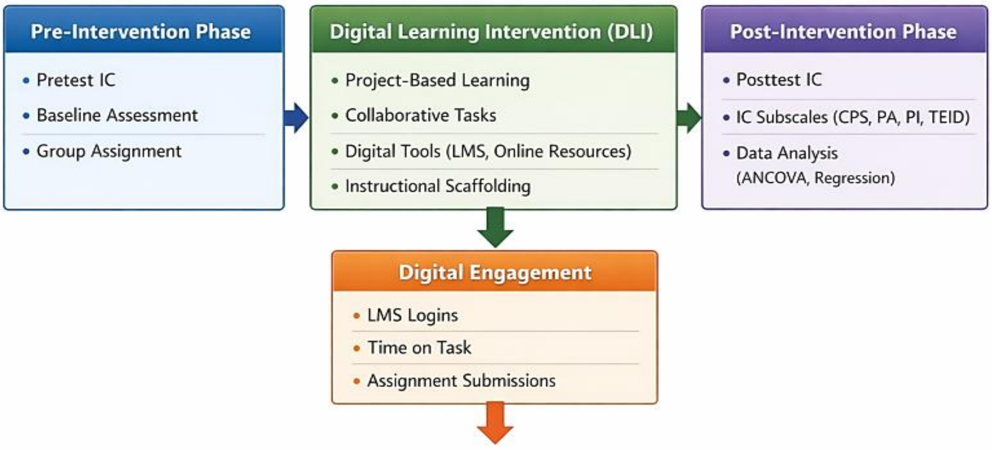

Figure 1. Structure of the DLI

A structured DLI lasting 12 weeks was delivered in a blended format combining online and face-to-face sessions. The intervention targeted four dimensions of IC: CPS, pedagogical adaptability, proactive initiative, and technology-enhanced instructional design. Participants engaged in project-based and collaborative tasks designed to develop these skills. All sessions followed a structured protocol to ensure consistency, and attendance and engagement were monitored to maintain adherence to the intervention plan.

The DLI was systematically designed around scaffolded instructional phases, progressing from orientation and collaborative skill-building to applied project development, simulation, and reflective evaluation. Each weekly session included clearly defined learning outcomes, guided digital activities, and structured interaction tasks aimed at progressively developing participants' IC across cognitive, pedagogical, and technological dimensions. The intervention design ensured alignment between instructional activities, targeted IC subcomponents, and digital tool integration to support consistent competence development throughout the 12-week period. The intervention was implemented following a standardized protocol to ensure instructional consistency and fidelity across sessions.

Ethical approval was obtained from the University Ethics Committee, and institutional permission was granted to conduct the intervention. Two intact groups were included due to administrative and scheduling constraints. The EG received the structured intervention, whereas the CG continued with the standard curriculum without additional digital enhancement. The detailed overview of weekly session focus, activities, and digital tools is can be seen in Table 3.

Table 3. Weekly schedule and activities of the DLI

Week	Focus	Activities	Tools/platforms
1	Introduction	Orientation, icebreaker tasks	Google Classroom, Zoom
2	Collaboration	Padlet & Mentimeter training, group discussions	Padlet, Mentimeter
3	CPS I	Individual case study, reflection	Google Docs, Kahoot
4	CPS II	Digital task design, peer feedback	Google Docs, Jamboard
5	Applied pedagogy	Lesson plan adaptation with tech	Learning management system (LMS), PowerPoint
6	Group project I	Project selection & planning	Zoom, Google Drive
7	Group project II	Implementation & documentation	Padlet, Mentimeter
8	Group project III	Peer review & iterative improvement	LMS, Google Docs
9	Simulation I	Design technology-enhanced lesson	LMS, Educational Software
10	Simulation II	Pilot presentation to peers	Zoom, Padlet
11	Reflection & feedback	Group reflection, instructor feedback	Google Forms, Jamboard
12	Final presentation	Final project presentation, posttest	LMS, Zoom

2.4. Instruments

IC was measured using an adapted 17-item IC scale grounded in prior research on educational innovative thinking competencies [34]. The scale employs a 5-point Likert format (1=strongly disagree, 5=strongly agree). Total IC scores range from 17 to 85, with higher scores indicating higher levels of IC. Subscale scores are calculated as the mean of items corresponding to each theoretical dimension.

The adaptation process followed established cross-cultural instrument adaptation guidelines. First, the original items were translated into Kazakh using forward translation by a bilingual educational researcher. Second, an independent bilingual expert performed back-translation to ensure semantic equivalence. Minor wording adjustments were made to reflect the pre-service teacher education context rather than in-service practice. Content validity was reviewed by two experts in teacher education and educational innovation. A pilot test (n=26) was conducted to ensure clarity and internal consistency before full-scale administration.

Internal consistency was reassessed in the present study. Cronbach's alpha coefficients demonstrated satisfactory reliability for the overall scale and all subscales (α=0.78-0.91). Construct validity was examined using confirmatory factor analysis to test the four-factor structure. The CFA results supported the proposed four-factor model corresponding to the theoretical dimensions of IC. Model fit indices indicated an acceptable fit to the data, providing evidence for the construct validity of the adapted scale in the context of pre-service teacher education. The final Kazakh-language version was administered anonymously one week prior to the intervention (pretest) and one week after the 12-week DLI (posttest). Participation was voluntary and responses did not affect academic grading, reducing potential social desirability bias. The full list of items, scoring procedures, and subscale allocation are provided in Table 4.

Table 4. IC scale

Dimension	Item no.	Statement
CPS	1	I carefully observe classroom situations and identify opportunities for improvement.
	2	I can generate multiple alternative solutions for educational challenges.
	3	I critically evaluate existing teaching approaches.
	4	I create new ideas to solve educational problems.
PA	5	I adapt lesson plans to new conditions or student needs.
	6	I change teaching strategies when I notice they are ineffective.
	7	I respond flexibly to feedback from colleagues and students.
	8	I adjust my actions to improve learning outcomes.
PI	9	I propose new ideas and solutions to improve the learning process.
	10	I actively participate in group projects and collaborative work.
	11	I initiate innovative activities in educational settings.
	12	I share my ideas with colleagues for joint improvement of teaching.
TEID	13	I use digital tools to create assignments and projects.
	14	I experiment with new technologies in teaching practice.
	15	I integrate digital tools into lesson planning and delivery.
	16	I evaluate the effectiveness of technology use and adjust my approaches.
	17	I implement innovative digital solutions to enhance the educational process.

2.5. Data analysis

The analytical strategy is summarized in Table 5. In this study, statistical analyses were conducted to examine the relationships between the key variables and to test the proposed hypotheses. Descriptive statistics and appropriate inferential techniques were applied to ensure the reliability and validity of the results.

Table 5. Data analysis strategy by research question

Research question	Statistical procedures
RQ1: Is participation in the DLI associated with differences in IC improvement compared to regular instruction?	- Baseline equivalence: independent samples t-tests (pretest IC, GPA) and chi-square tests (gender, DL level) - Analysis of covariance (ANCOVA): posttest IC as dependent variable, group as fixed factor, pretest IC as covariate - Assumptions: normality (Shapiro–Wilk), homogeneity of variance (Levene's test), homogeneity of regression slopes - Effect size: partial η^2, Cohen's d.
RQ2: Which IC dimensions demonstrate the greatest improvement in the intervention group?	- ANCOVA models were conducted for total IC and each IC subscale (posttest scores as dependent variables; corresponding pretest scores as covariates). - Bonferroni correction was applied to control for multiple comparisons. - Effect sizes (partial η^2 and Cohen's d) were reported.
RQ3: To what extent do digital engagement variables predict changes in IC, and does this relationship differ between the EG and the CG?	Hierarchical multiple regression predicting posttest IC: - Step 1–Pretest IC and group (0=CG, 1=EG) - Step 2–Engagement indicators (LMS logins, submissions, time-on-task) - Step 3–Interaction terms (Group × each engagement variable). Continuous predictors mean-centered; VIF assessed.

3. RESULTS

The descriptive statistics (DS) presented in Table 6 indicate that the two groups were comparable at baseline, suggesting an adequate initial equivalence for further analysis. After the intervention, a clear divergence between the groups can be observed, with more pronounced changes in the EG compared to the CG. This pattern suggests that participation in the DLI may be associated with more substantial development of IC. These preliminary trends provide supportive evidence for the subsequent inferential analyses, which test the statistical significance and robustness of these differences.

Adjusted posttest means, effect sizes, and statistical significance for total IC are summarized in Table 7. The ANCOVA results indicate that participation in the DLI was associated with improved IC outcomes. The adjusted posttest estimates highlight the advantage of the intervention group over the CG, suggesting that the observed differences remained significant after controlling for baseline competence levels. The effect size was large according to conventional benchmarks, indicating a statistically significant and educationally meaningful intervention impact.

Table 6. DS for IC at pretest and posttest

Group	N	Pretest IC (M±SD)	Posttest IC (M±SD)
EG	78	64.5±6.20	72.5±6.50
CG	78	64.3±6.15	65.8±6.38
Total	156	64.4±6.18	69.2±6.44

Table 7. ANCOVA results for total IC score

Group	Adjusted posttest IC (M±SE)		
EG	72.5±0.73		
CG	65.8±0.73		
Group effect			
F(1,153)	*p*	Partial η²	Cohen's d
42.17	<.001	.216	1.05

Adjusted posttest means, ANCOVA statistics, and effect sizes are summarized in Table 8. The ANCOVA results demonstrate that, after controlling for baseline levels of IC, the EG outperformed the CG across all four subscales. These findings indicate that the DLI was associated with consistent improvements in multiple dimensions of IC rather than affecting a single isolated domain. The largest effect was observed in CPS, suggesting that the intervention may have supported the development of flexible and innovative approaches to educational challenges. Technology-enhanced instructional design (TEID) also demonstrated a substantial effect, indicating that structured exposure to digitally enriched pedagogical practices may effectively support teachers' ability to integrate and evaluate technology in instructional contexts.

Table 8. ANCOVA results for IC subscales

IC Dimension	EG adjusted mean±SE	CG adjusted mean±SE	F(1,153)	*p*	Partial η²	Cohen's d
CPS	18.5±0.28	16.2±0.28	33.78	<.001	0.181	0.94
PA	18.1±0.29	16.5±0.29	18.97	<.001	0.110	0.63
PI	18.8±0.33	17.0±0.33	14.88	<.001	0.089	0.62
TEID	17.6±0.26	15.8±0.26	47.94	<.001	0.239	0.78

The hierarchical regression results are presented in Table 9. In the first step, pretest IC and group membership were entered as predictors. Pretest competence emerged as a strong predictor of the posttest outcome, indicating substantial temporal stability, while group membership remained significant after accounting for baseline levels, indicating higher posttest scores for participants in the intervention group. In the second step, the inclusion of digital engagement variables improved the explanatory power of the model. LMS login frequency, number of submissions, and time-on-task were all positively associated with posttest competence, suggesting that greater participation in digital learning activities was linked to stronger outcomes beyond initial differences. In the final step, interaction terms between group membership and engagement indicators were added. Significant interactions were observed for LMS logins and time-on-task, indicating that the relationship between digital engagement and posttest IC differed between the intervention and CGs. The interaction involving submissions approached statistical significance, suggesting a similar but weaker pattern. The final model explained 48.8% of the variance in posttest IC.

Table 9. Hierarchical regression analysis predicting posttest IC

Step	Predictor	β	t	*p*	VIF
Step 1					
	Pretest IC	0.58	9.51	<.001	1.34
	Group (EG vs CG)	0.29	5.02	<.001	1.18
Model statistics	ΔR^2=0.392				
Step 2					
	LMS logins	0.17	2.88	.005	1.26
	Assignment submissions	0.14	2.33	.021	1.22
	Time on task	0.16	2.62	.010	1.29
Model statistics	ΔR^2=0.067				
Step 3					
	Group × LMS logins	0.12	2.18	.031	1.31
	Group × submissions	0.10	1.94	.054	1.28
	Group × time on task	0.13	2.27	.025	1.33
Model statistics	ΔR^2=0.029				

Participation in the DLI was associated with statistically significant improvements in overall IC and its four subscales in Table 10. The effect for total IC was large (Cohen's d=1.05, partial η^2=0.216), indicating both statistical and educationally meaningful impact. Subscale analyses revealed that CPS and TEID benefited most from the intervention (Cohen's d=0.94 and 0.78, respectively), while PA and PI showed moderate improvements (Cohen's d≈0.62–0.63). These effect sizes demonstrate that the DLI promoted multidimensional competence rather than improvements in a single domain.

Hierarchical regression analyses further indicated that engagement with digital learning tools-LMS logins, assignment submissions, and time-on-task-positively predicted IC gains. Significant interactions between group membership and engagement for LMS logins and time-on-task suggest that the structured DLI amplified the benefits of active digital participation, particularly in the EG. Contextually, the stronger gains in CPS and TEID likely reflect the intervention's emphasis on project-based tasks and technology integration, whereas the more moderate improvements in pedagogical adaptability (PA) and proactive initiative (PI) indicate that developing adaptive and proactive skills may require additional pedagogical support or longer-term exposure.

Table 10. Effect sizes of the DLI on IC outcomes

Outcome variable	Partial η^2	Cohen's d	Effect magnitude
Total IC	.216	1.05	Large
CPS	.181	0.94	Large
PA	.110	0.63	Medium
PI	.089	0.62	Medium
TEID	.239	0.78	Large

4. DISCUSSION

The present study examined whether a structured DLI is associated with improvements in IC among PSTs and explored the role of digital engagement in this process. Overall, the findings indicate that participation in the DLI was linked to meaningful multidimensional improvements across all four IC subscales. Digital engagement also emerged as a notable factor supporting IC growth, particularly within the intervention group. These results address the previously identified gap regarding the scarcity of empirically validated models connecting structured digital pedagogy with multidimensional IC in teacher education [35].

From a theoretical perspective, the findings extend existing models of TPD by demonstrating that IC can be developed not only through long-term experiential learning and reflective practice, as emphasized in traditional TPD frameworks, but also through structured, digitally mediated learning environments. The results support competency-based perspectives of teacher learning, which conceptualize professional growth as the integration of cognitive, motivational, and behavioral dimensions. In this sense, digitally enriched learning environments function not only as supplementary tools but also as active mechanisms for competence development by embedding pedagogical scaffolding, collaborative problem-solving, and sustained engagement with digital technologies. Accordingly, the study contributes to rethinking TPD models by positioning structured DLIs as drivers of innovation-oriented professional competence formation in PSTs.

The findings are consistent with prior research showing that digital transformation in higher education can foster higher-order competencies when supported by structured pedagogical design rather than ad hoc technology use [36]–[38]. Previous studies reported positive associations between DLI and CPS, PA, and instructional innovation [39], [40]. However, many relied on correlational designs or narrowly focused on technological skills. The present study extends this literature by demonstrating that a structured, multi-component DLI can support not only technology-related competence but also broader innovation-oriented dimensions such as PI and PA [41], [42].

The observed improvements across all IC dimensions suggest that IC functions as an integrated construct rather than a collection of isolated skills. These findings further highlight the importance of developing IC among PSTs, as it has a direct impact on teaching quality, student learning outcomes, and broader educational reform. Strengthening IC enables future teachers to design more engaging, technology-enhanced, and learner-centered instruction, which improves classroom interaction and supports deeper student understanding. Moreover, IC fosters adaptability and reflective practice, which are essential for responding to rapidly changing educational environments and integrating digital tools effectively. At the system level, enhancing IC among PSTs contributes to sustainable educational reform by preparing teachers who can actively implement and innovate within modern competency-based curricula. Medium to large effects across dimensions reflect consistent and meaningful development following the DLI. These results support theoretical models framing IC as a dynamic interplay between cognitive, motivational, and technological domains [43], [44]. Moreover, although grounded in the Kazakhstani context, the findings are particularly relevant in light of the country's ongoing higher education modernization reforms and its strategic emphasis on digital transformation and competency-based teacher education. The country's national policies increasingly prioritize the integration of digital technologies and innovation skills in teacher preparation programs, making the development of IC among PSTs a key educational objective. In this context, the findings provide evidence-based insights that can inform the refinement of national teacher education standards, particularly in strengthening structured DLIs. Furthermore, while grounded in Kazakhstan, the results also offer implications for other educational systems undergoing similar transitions toward digitally enhanced and competency-driven teacher education models.

The intervention was effective likely because it combined collaborative learning, project-based tasks, and sustained digital engagement, which together supported multidimensional IC. This effect can be further explained through the interaction of several pedagogical mechanisms. Project-based and collaborative learning activities likely enhanced cognitive engagement by requiring PSTs to actively construct knowledge and apply it in authentic contexts, which aligns with constructivist learning theory. At the same time, sustained digital engagement may have strengthened motivational aspects of learning by promoting autonomy, continuous participation, and iterative feedback, all of which are critical for competence development. The integration of instructional scaffolding within the DLI likely supported the gradual progression from guided practice to more independent and innovative instructional design. Together, these elements created a coherent learning environment in which technological, pedagogical, and motivational factors interacted synergistically, thereby facilitating multidimensional growth in IC.

From an educational practice perspective, these findings suggest that teacher education programs should move beyond isolated digital skills training toward structured, pedagogically designed DLIs that intentionally integrate collaboration, reflection, and sustained digital interaction. For policy, the results support the inclusion of structured DC frameworks within teacher education standards, emphasizing not only technical proficiency but also innovation-oriented and collaborative competencies. This alignment can inform curriculum reforms and professional development guidelines that prioritize evidence-based digital pedagogy as a core component of teacher preparation. From a theoretical perspective, the findings further support competency-based and transformative teacher professional development frameworks, which emphasize the integration of cognitive, motivational, and collaborative dimensions of learning within digitally mediated environments. In conclusion, the study highlights that carefully designed DLI, combined with pedagogical intentionality and sustained engagement, can effectively foster innovation-oriented professional competencies in PSTs. These findings provide practical guidance for integrating structured digital approaches into teacher education, moving beyond technical training toward cultivating multidimensional IC.

5. LIMITATIONS

Several limitations should be considered when interpreting the findings of this study. First, the quasi-experimental design with non-randomized intact groups limits the ability to draw strong causal conclusions. Although baseline equivalence was statistically assessed and controlled through ANCOVA procedures, unmeasured confounding variables may have influenced the observed differences between groups. Second, the study was conducted within a single institution and involved third-year pre-service teachers from one teacher education program. This contextual specificity may limit the generalizability of the findings to other institutions, disciplines, or educational systems. Future multi-site studies would strengthen external validity. Third, IC was measured using self-reported survey data. Complementing self-report scales with performance-based assessments or observational measures could provide a more comprehensive evaluation of competence development. Fourth, digital engagement was operationalized through LMS-based indicators (login frequency, number of submissions, and time-on-task). Although these metrics offer objective behavioral data, they may not fully capture the qualitative depth of engagement or cognitive processing. More fine-grained analytics or mixed-method approaches may clarify the mechanisms linking digital participation and competence growth. In light of these limitations, future research should employ multi-site or randomized designs and integrate performance-based or observational measures alongside self-reports. For practice, structured DLIs combining project-based tasks, collaboration, and technology integration are recommended, while policy should support IC as a core outcome in pre-service teacher education curricula.

6. CONCLUSION

This study examined the association between a structured DLI and the development of IC among PSTs. The findings suggest that participation in the 12-week intervention was linked to multidimensional improvements in IC, including CPS, PA, PI, and TEID. In addition, digital engagement indicators were found to predict competence growth, with stronger effects observed within the intervention context. These results indicate that IC development may benefit from pedagogically intentional digital integration rather than technology exposure alone. From a practical perspective, these results suggest that teacher education programs should move beyond isolated digital skills training toward systematically designed digital learning experiences. Such approaches can be implemented through project-based and collaborative activities in which PSTs design technology-enhanced lesson plans aligned with curriculum standards. The integration of LMS into coursework-through structured assignments, peer feedback, and reflective activities-can support sustained engagement. Instructional scaffolding may be operationalized through guided templates, rubrics, and progressively complex tasks, while analytics-based monitoring can enable timely feedback and targeted support. In addition, assessment of IC can be embedded into course evaluation through performance-based tasks capturing creativity, adaptability, and technology integration skills.

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C : **C**onceptualization
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O : Writing - **O**riginal Draft
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Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The corresponding author may provide study data upon reasonable request.

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