Digital literacy development of vocational college teachers: An industry-integrated TPACK framework and intervention study

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Digital transformation is reshaping vocational education, creating an urgent demand for teachers' digital literacy, particularly the integration of digital tools and alignment with evolving industry standards. Studies, however, often lack theoretical integration of pedagogical, technological, and industry components; robust longitudinal validation; and contextualized insights into implementation. To address these gaps, an integrated framework was developed by synthesising the technological pedagogical content knowledge (TPACK) framework with industry–education integration principles. A quasi-experimental pretest-post-test matched-group design, complemented by systematic quantitative analyses, was implemented at two comparable provincial vocational colleges in Central China, involving stratified random sampling of 115 full-time teachers per group. Baseline equivalence across all dimensions was confirmed. Following a 10-week intervention, substantial improvements were observed in the experimental group, particularly in industry–pedagogical content knowledge and digital–collaborative content knowledge. Multiple regression analyses further demonstrated robust intervention effects after controlling for demographic variables, with significant interactions between intervention and teacher characteristics. The study contributes threefold: theoretically, by advancing TPACK through industry–education integration framework, establishing longitudinal methodological foundations, and enriching contextual understanding; practically, by providing evaluation tools, modular training guidelines, and localised implementation strategies; and internationally, by demonstrating transferability across institutional arrangements, digital maturity levels, and resource conditions.

Implications for practice or policy:
- Vocational education leaders can enhance teachers' digital literacy by implementing a four-layer integrated evaluation framework aligned with industry standards.
- Faculty developers may support professional growth through modular training pathways integrating digital tools with industry applications.
- Instructional designers can develop subject-specific digital resources leveraging industry–education integration principles.
- Institutional policymakers can foster sustainable development by establishing digital collaboration platforms locally.

Keywords: digital literacy, industry-education integration, intervention study, teacher professional development, TPACK, vocational education

Introduction

Digital transformation is reshaping vocational education, requiring new approaches to teacher development and industry alignment (Jiang et al., 2024; Wang & Si, 2023; Zhao et al., 2023). This transformation is evident in smart manufacturing integration, digital service innovation and shifting workplace competencies, demanding comprehensive *digital literacy* that goes beyond basic technical skills. Digital literacy here refers to integrating digital tools, evaluating information, solving problems and aligning teaching with industry needs (McGrath & Yamada, 2023; Nikou & Aavakare, 2021).

Existing frameworks guiding educators' digital literacy show notable limitations in vocational contexts. Although the European digital competence framework for educators (Caena & Redecker, 2019) and the *International Society for Technology in Education Standards* (Crompton, 2017) provide general educational guidance, neither adequately addresses vocational specificity. The *technological pedagogical content knowledge (TPACK)* framework (Mishra & Koehler, 2006; Schmid et al., 2021), despite its value in technology–pedagogy integration, requires substantial adaptation for vocational settings where rapid technological change demands current industry knowledge beyond its traditional scope (Spöttl & Windelband, 2021; Wheelahan & Moodie, 2025). Despite attempts to connect TPACK with workplace learning (Tondeur et al., 2020), the lack of an integrated framework continues to limit industry-aligned curriculum development (Gong, 2024). While recent interventions have explored professional development approaches (Al-Adwan et al., 2024; Al-Adwan et al., 2025; Yuniarti et al., 2024), methodological limitations in duration and measurement persist (Romero-Hall & Jaramillo Cherrez, 2023; Tondeur et al., 2019). This disconnection between theoretical frameworks and industry needs is particularly challenging in China, where rapid industrial digitalisation demands stronger alignment between teaching and workplace requirements.

Despite progress, three critical gaps persist: insufficient theoretical integration of pedagogy and industry components, limited empirical validation through longitudinal studies and inadequate contextual understanding of implementation challenges. These gaps highlight the urgent need for an integrated framework and empirical evidence to guide vocational teachers' digital literacy development.

To address these gaps, this study developed and validated an integrated framework that synthesises TPACK theory (Mishra & Koehler, 2006) with *industry–education integration principles* (Gong, 2024; McGrath & Yamada, 2023; Spöttl & Windelband, 2021). Using a four-layer approach, it bridges theoretical foundations with operational indicators, providing a comprehensive model for vocational teachers' digital literacy development. Specifically, the study addressed three research questions:

1. What are the baseline differences, if any, between the experimental and control groups prior to the intervention?
2. To what extent does the intervention enhance the digital literacy of teachers in the xperimental group?
3. To what extent do intervention effects persist after accounting for teacher characteristics?

The research questions were formulated to ensure methodological rigour and validity. The first addressed baseline equivalence, a prerequisite for credible quasi-experimental inference. The second evaluated intervention effectiveness, while the third examined persistence and generalisability across teacher profiles, thereby extending practical relevance. To answer these questions, a quasi-experimental pretest–post-test matched-group design (115 teachers per group) was adopted. This design, complemented by systematic quantitative analyses including group comparisons, regression modelling with demographic controls and interaction effects, and various robustness checks, enables robust causal inference while maintaining ecological validity.

Building on methodological rigour, the study aimed to make three key contributions: a theoretical advancement in integrating TPACK theory with industry-education integration principles, establishing longitudinal methodological foundations and enriching contextual understanding within vocational settings; a practical contribution in developing evaluation tools, modular training guidelines and localised implementation strategies for systematic application; and an international perspective in demonstrating framework transferability across institutional arrangements, digital maturity levels and resource conditions.

Digital literacy development in Chinese vocational education: Theoretical integration and industry-driven challenges

Reframing digital literacy in vocational education

Digital transformation driven by big data and emerging technologies is reshaping vocational education and redefining teachers' digital literacy needs (Jiang et al., 2024). Digital literacy, in this context, is conceptualised as the ability to effectively integrate digital tools, critically evaluate information, solve complex problems and align instructional practices with evolving industry standards (McGrath & Yamada, 2023; Nikou & Aavakare, 2021; Yondler & Blau, 2023). This change stems from three interrelated trends: accelerating industrial digitalisation requiring workforce alignment with emerging standards (Wang & Si, 2023); increasingly complex digital workplaces demanding competencies beyond basic skills (Zhao et al., 2023); and vocational practices transformed by smart manufacturing and digital services, prompting pedagogical innovation (Hanelt et al., 2021). These trends collectively reshape the concept of digital literacy in vocational education, necessitating a fundamental reconceptualisation of teachers' professional development. The rapid digital shift exposes gaps in teachers' digital preparedness, potentially compromising pedagogical effectiveness and student readiness for technology-driven labor markets, thus necessitating enhanced teachers' digital literacy.

From generalist models to industry–education aligned digital literacy

Current digital literacy frameworks prove insufficient for vocational education's unique demands. The European digital competence framework for educators defines educators' digital literacy across six areas (e.g., professional engagement, digital resources, teaching and learning, assessment, empowering learners and facilitating digital learning environments) (Caena & Redecker, 2019), while the International Society for Technology in Education Standards outline technology integration focusing on learning design and student empowerment (Crompton, 2017). However, both frameworks inadequately address vocational specificity. The TPACK framework (Mishra & Koehler, 2006), though conceptualising technology-pedagogy-content integration, requires substantial adaptation for vocational contexts. While research shows TPACK's influence on lesson planning and technology integration (Schmid et al., 2021), the rapid pace of technological change requires teachers to maintain current industry knowledge and practices beyond TPACK's traditional scope (Spöttl & Windelband, 2021; Wheelahan & Moodie, 2025). Although progress connects TPACK with workplace learning (Tondeur et al., 2020), the absence of a comprehensively integrated framework limits educators' ability to develop industry-aligned curricula (Gong, 2024).

Challenges and gaps: Towards contextually valid digital literacy approaches

Empirical studies have tested quantitative interventions through professional development programmes (Al-Adwan et al., 2025), blended learning experiments (Al-Adwan et al., 2024) and technology-enhanced training (Yuniarti et al., 2024). However, many interventional studies suffer from methodological limitations including insufficient intervention duration and inadequate measurement of effectiveness. Statistical analyses have revealed that sustained digital literacy development requires systematic implementation and robust measurement approaches (Romero-Hall & Jaramillo Cherrez, 2023; Tondeur et al., 2019). In Chinese vocational education, scarce longitudinal research and reliance on cross-sectional surveys limit understanding of digital literacy development. Furthermore, few interventions have embedded TPACK in industry-integrated training, restricting insights on maintaining workplace-aligned competencies.

Despite progress, three key gaps persist. Theoretically, models inadequately integrate pedagogical, technological, and industry-education components for holistic vocational digital literacy (Spöttl & Windelband, 2021; Wheelahan & Moodie, 2025). Methodologically, rigorous longitudinal studies tracking sustained, industry-aligned teacher development are rare (Al-Adwan et al., 2024; Al-Adwan et al., 2025; Yuniarti et al., 2024). Contextually, research on China's vocational education system, especially policy-industry alignment, remains limited. These gaps highlight the urgent need to deepen understanding and craft practical strategies for digital literacy enhancement amid rapid industrial change demanding innovative teacher development.

An integrated four-layer theoretical framework for vocational teachers' digital literacy development

To address the gaps identified above, especially in the integration of pedagogical, technological and industry-education components for digital literacy in vocational contexts, this study developed and validated an integrated theoretical framework that synthesises TPACK theory and the industry-education integration principles. The novelty of this framework lies in its systematic progression through four layers: theoretical foundation, dimensional reconstruction, functional operationalisation and assessment indicators.

At Layer 1, the theoretical foundation combines TPACK theory (Mishra & Koehler, 2006) with industry-education integration principles to delineate core elements. TPACK theory highlights technological knowledge (digital tool mastery), pedagogical knowledge (teaching methods) and content knowledge (subject expertise). The industry-education integration principles (Gong, 2024; McGrath & Yamada, 2023; Spöttl & Windelband, 2021) emphasise industry standards (workplace requirements), workplace practice (authentic learning) and enterprise resources (industry collaboration). These components form the foundation for subsequent layers, supporting the synthesis of knowledge, application and development constructs. Building on Layer 1, Layer 2 synthesises the core components into three integrated dimensions. The *knowledge dimension* merges TPACK's technological knowledge with industry-specific content knowledge, focusing on digital and professional foundations. The *application dimension* combines pedagogical knowledge with workplace practices, reflecting the integration of teaching methods and industry tools. The *development dimension* synthesises innovative teaching approaches with industry collaboration, representing the highest level of integration and development.

Continuing from Layer 2, Layer 3 maps each dimension into corresponding functional components. The knowledge dimension translates into technical knowledge function. The application dimension operationalises into industry pedagogy function and content dynamic function. The development dimension corresponds to teaching innovation function and industry collaboration function. These functional components transform theoretical constructs into measurable capacities. Drawing from the functional components of Layer 3, Layer 4 defines five key indicators that operationalise the theoretical framework. *Digital technical knowledge* (DTK) focuses on technological proficiency, while *industry-pedagogical content knowledge* (IPCK) emphasises teaching method alignment with industry practices. *Dynamic content construction knowledge* (DCCK) addresses content evolution and updating, *digital teaching innovation competence* (DTIC) reflects innovative integration capacity and *digital industry-college collaboration* (DICC) measures collaborative development competence. Figure 1 illustrates the four-layer integrated framework progression from theoretical foundation to assessment indicators, providing a comprehensive model for examining vocational teachers' digital literacy development within the context of vocational education and laying the theoretical foundation for subsequent empirical investigation.

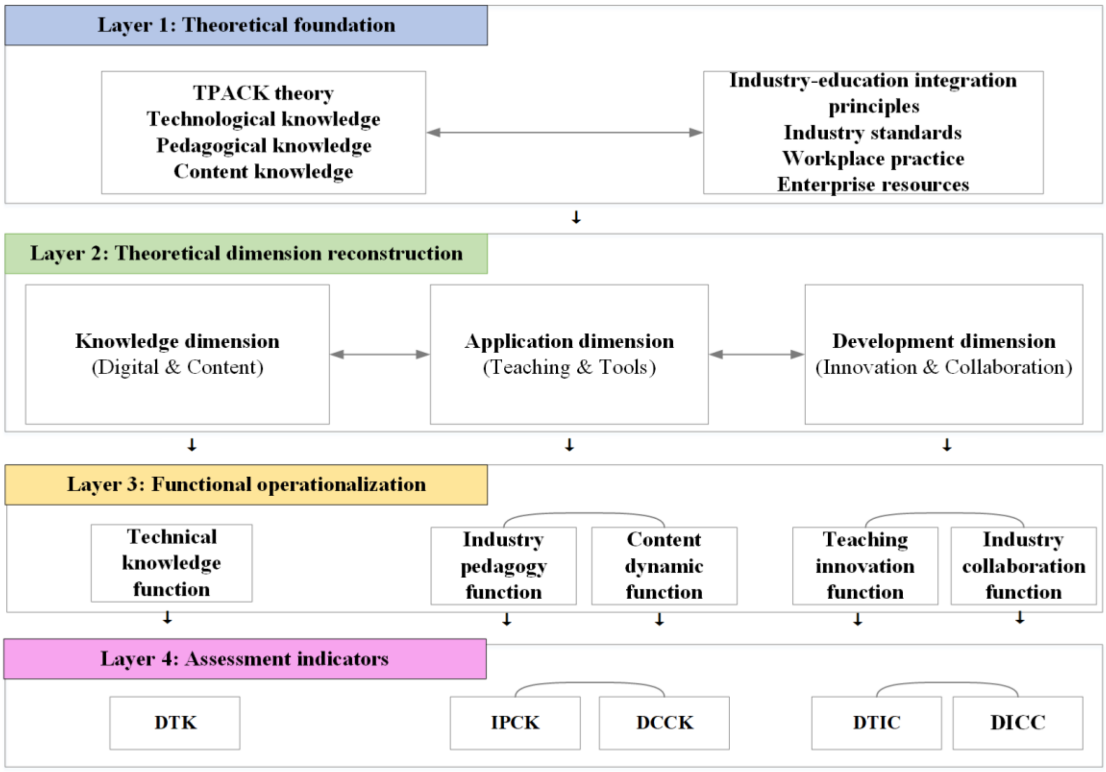

Figure 1. An integrated four-layer theoretical framework of digital literacy development for vocational teachers

Note. DTK = digital technical knowledge; IPCK = industry-pedagogical content knowledge; DCCK= dynamic content construction knowledge; DTIC = digital teaching innovation competence; DICC = digital industry-college collaboration.

Methods

Research design

A quasi-experimental pretest–post-test matched-group design was employed over a 10-week intervention to address gaps in the literature, particularly the lack of longitudinal studies, while enabling approximate causal inference and maintaining ecological validity (Creswell & Creswell, 2017; Matthay & Glymour, 2020). The study framework and design are illustrated in Figure 2, showing the independent variable (intervention programme), the dependent variable (digital literacy with five dimensions: DTK, IPCK, DCCK, DTIC, DICC) and control variables. Gender and subject area were recorded as covariates given their significant influence on teachers' technology adoption patterns (Al-Adwan et al., 2025) and pedagogical integration of digital tools (Jiang et al., 2024). The design addressed three primary research questions concerning the intervention's effectiveness on teachers' digital literacy development. Data were collected at two time points using parallel versions of the 21-item Five-Dimension Digital Literacy Scale (FDDLS) that we developed: pre-intervention assessment (FDDLS_A) and post-intervention assessment (FDDLS_B). This design allowed for the assessment of between-group differences and within-group changes across the intervention period.

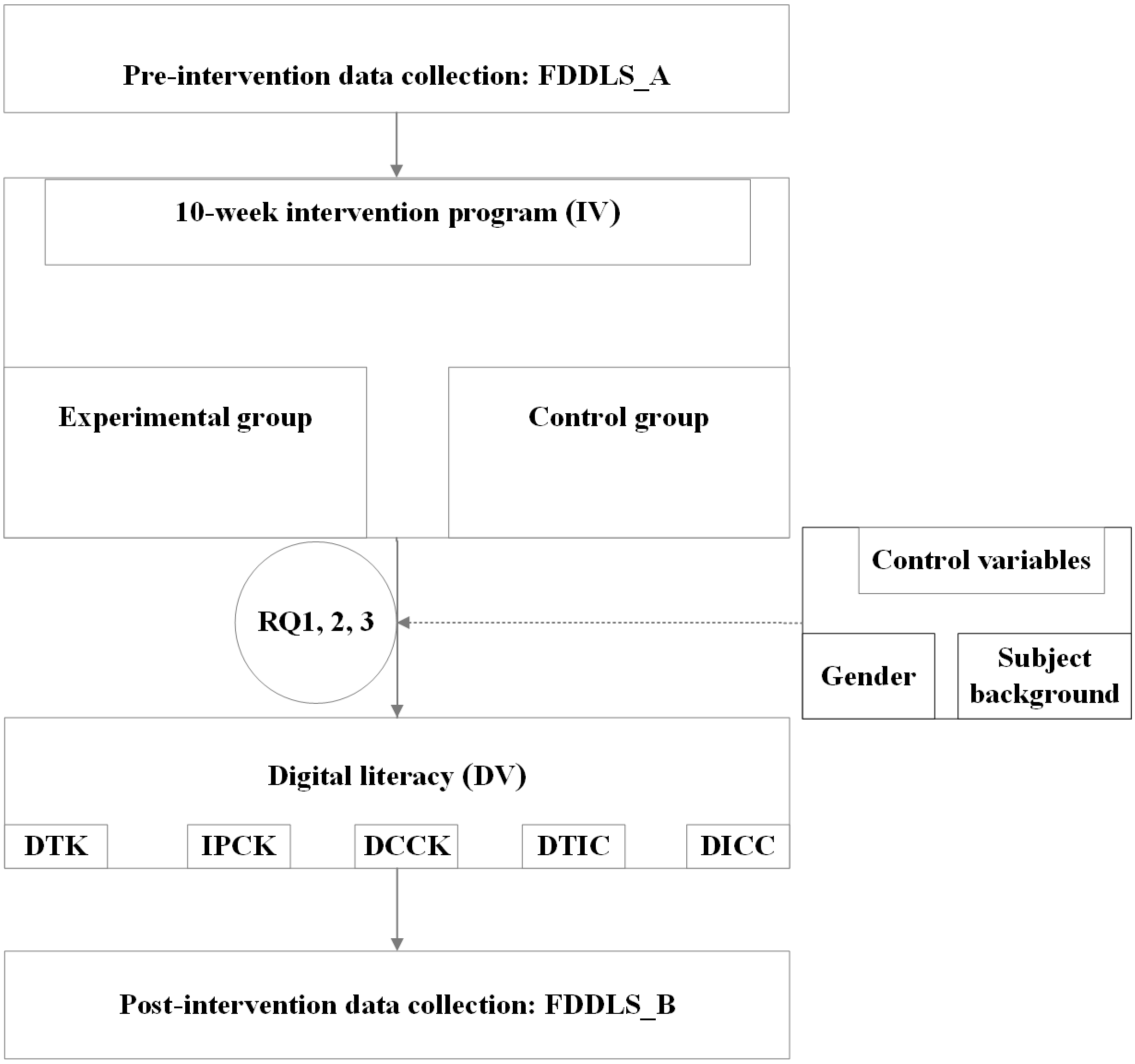

Figure 2. Conceptual framework of this study

Note. RQ = research question; IV = intervention programme (independent variable); DV = digital literacy (dependent variable); FDDLS = five-dimension digital literacy scale administered at pre-intervention (A) and post-intervention (B). Control variables include gender and subject background.

Participants

Sample size was determined based on the 21-item FDDLS, following the recommended subject-to-item ratio of 4:1–10:1 (Hair et al., 2019), yielding a minimum of 84 participants per group. Allowing for 15%–20% attrition, 115 participants per group were targeted. At the institutional level, purposive sampling identified eligible vocational colleges from 12 provincial-level demonstration institutions in Central China (government-designated pilot colleges recognised for their educational quality and digital reform initiatives). Two vocational colleges were selected via propensity score matching (Rosenbaum, 2023) to ensure comparability in size (approximately 9,000 students, ±500), programme offerings (over 80% overlap), digital infrastructure (±5% of annual budget) and faculty composition. At the teacher level, 386 full-time faculty with ≥3 years of teaching experience and baseline digital literacy were screened. Stratified random sampling was conducted across subject areas – science and engineering, business management, arts – and gender. Following internal invitations, 115 participants per group were randomly selected to ensure balanced representation across departments, subject areas and gender.

Research instruments

Vocational teachers' digital literacy was measured with the FDDLS. Following DeVellis and Thorpe (2021), development involved theory-driven construction grounded in TPACK and industry–education integration, expert review (*N* = 20) and pilot testing (*N* = 30), exploratory factor analysis (Sample A = 271) and confirmatory factor analysis (Sample B = 271) using responses from 542 teachers across 20 vocational colleges in 10 provinces. Two parallel forms (A, B) were designed for pretest and post-tests, each with 21 items across five domains–DTK, IPCK, DCCK, DTIC, DICC–rated on a 5-point Likert scale. To maintain test authenticity and minimise practice effects, Form B was developed with slight modifications for post-test assessment, while psychometric equivalence was confirmed (r = .89, p < .001). Counterbalanced administration to 120 teachers further confirmed equivalence.

Both forms demonstrated sound psychometric properties: composite reliability = .83–.87; average variance extracted = .55–.63; factor loadings = .667–.901. Confirmatory factor analysis indicated good fit (χ^2/df = 1.55; comparative fit index = .967; normed fit index = .914; root-mean-square error of approximation = .045), consistent with recommended cutoffs (Keith, 2019; McNeish & Wolf, 2023). Convergent validity was confirmed (all loadings > .50, p < .001), and discriminant validity was supported using the Fornell–Larcker criterion (Fornell & Larcker, 1981). Internal consistency reliability was also strong (Cronbach's α = .83–.87 across domains). These results support the suitability of both FDDLS forms for assessing vocational teachers' digital literacy in technology-enhanced contexts.

Intervention programme and implementation

The intervention followed a three-phase design (Figure 3). In the pre-intervention phase (February–March 2024), framework validation and pilot testing were conducted. An expert panel (*N* = 10; four digital education specialists, three industry professionals, three vocational educators) validated the framework through two Delphi rounds (Cohen's κ = 0.87; consensus > 85%). A four-week pilot with 32 vocational teachers (*M* teaching experience = 8.5 years, *SD* = 3.2) employed quantitative evaluation: (a) pre–post competency assessments (α = .88), (b) standardised observations (n = 16, intraclass correlation coefficient = .86) and (c) structured surveys (response rate = 96%). Findings informed refinements in delivery (practical exercises: 30 → 45 minutes; weekly contact hours: 3 → 4; navigation rating: 3.2 → 4.1/5.0). Baseline data were then collected using FDDLS Form A, administered by trained assistants under standardised protocols (> 95% adherence). Demographic data were collected through standardised questionnaires covering teaching experience, educational background and subject area. Teaching practice was documented using classroom observation protocols, teaching portfolios and digital competency assessment forms.

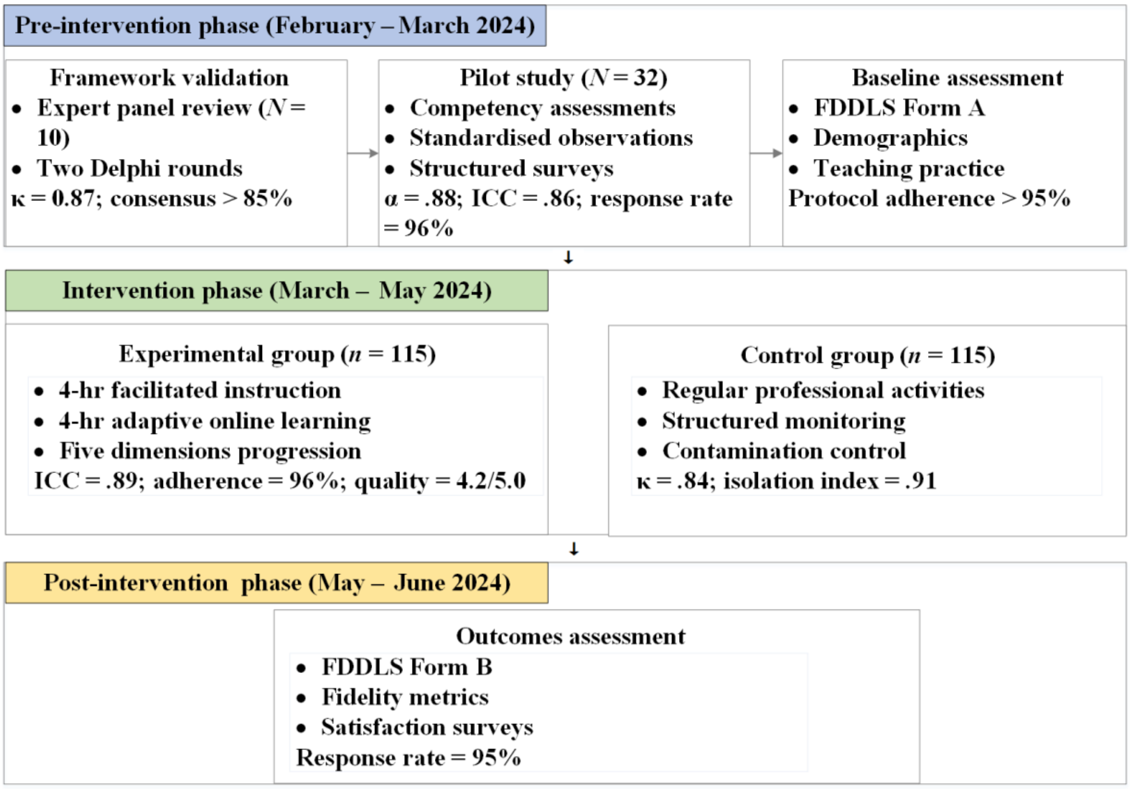

Figure 3. Three-phase implementation design and quality control metrics of the digital literacy intervention programme
Note. ICC = intraclass correlation coefficient.

During the 10-week intervention (March–May 2024), the experimental group (*n* = 115) participated in theoretically grounded weekly sessions integrating TPACK and industry–education integration principles (Gong, 2024; Mishra & Koehler, 2006). Each week's delivery combined 4 hours of facilitated instruction with 4 hours of adaptive online learning (Kasperski et al., 2022). The intervention content progressed systematically through five dimensions: DTK (Weeks 1–2) emphasised technology skills through hands-on training; IPCK (Weeks 3–4) focused on industry-oriented curriculum development; DCCK (Weeks 5–6) addressed content optimisation; DTIC (Weeks 7–8) developed innovative teaching approaches; and DICC (Weeks 9–10) enhanced industry-education collaboration capabilities. Throughout the intervention, data collection followed a structured schedule to ensure rigour and comparability: weekly teaching logs and activity records, bi-weekly standardised classroom observations and monthly implementation fidelity checks. Implementation fidelity was continuously monitored (overall intraclass correlation coefficient = .89), and classroom observations showed high inter-rater reliability (observer intraclass correlation coefficient > .85) across content adherence (96%), delivery quality (*M* = 4.2/5.0) and participant engagement (*M* = 3.8, *SD* = 0.4 hours/week). Table 1 summarises dimension-specific objectives, content, strategies and implementation metrics (adherence rates: 92%–97%; quality ratings: 3.9–4.3/5.0).

Table 1
Five-dimension intervention implementation framework

Dimension	Training objectives	Core content	Implementation strategies	Theoretical support
DTK (Weeks 1–2)	1. Master educational technology application skills; 2. Develop digital resource	1. Educational technology tools application; 2. Digital resource design and development;	1. Technical tools hands-on training; 2. Group collaborative development;	Mishra & Koehler (2006); Tondeur et al. (2020)

Dimension	Training objectives	Core content	Implementation strategies	Theoretical support
	development literacy; 3. Enhance digital pedagogical competence.	3. Information-based teaching platform usage; 4. Digital learning resource repository development.	3. Mentor-guided practice; 4. Outcome demonstration and peer review.	
IPCK (Weeks 3–4)	1. Enhance curriculum development ability; 2. Form industry-oriented awareness; 3. Master content reconstruction methods.	1. Industry development trend analysis; 2. Professional competency mapping; 3. Curriculum content reconstruction design; 4. Industry-aligned resource optimisation.	1. Industry expert lectures; 2. Case study analysis; 3. Project practice design; 4. Results presentation.	Gong (2024); Spöttl & Windelband (2021)
DCCK (Weeks 5–6)	1. Establish systematic update mechanism; 2. Enhance content optimisation ability; 3. Cultivate continuous improvement awareness.	1. Industry information tracking methods; 2. Content update strategies; 3. Resource maintenance protocol; 4. Quality evaluation improvement.	1. Special topic discussions; 2. Best practice sharing and research; 3. Collaborative inquiry practice; 4. Feedback improvement optimisation.	Al-Adwan et al. (2024); McGrath & Yamada (2023)
DTIC (Weeks 7–8)	1. Enhance teaching innovation ability; 2. Master blended teaching; 3. Cultivate innovative practice ability.	1. Teaching model innovation design; 2. Blended teaching implementation; 3. Digital pedagogy integration; 4. Teaching evaluation reform.	1. Innovation case analysis; 2. Instructional design workshop; 3. Teaching practice demonstration; 4. Peer evaluation feedback.	Ortner et al. (2024); Yuniarti et al. (2024)
DICC (Weeks 9–10)	1. Enhance industry-education collaboration capacity; 2. Master project management methods; 3. Strengthen school-enterprise cooperation.	1. Basic project management methods; 2. Industry-education partnership framework; 3. Collaborative education model innovation; 4. Practical teaching optimisation.	1. Project practice operation; 2. School-enterprise cooperation discussion; 3. Achievement display and exchange; 4. Best practice dissemination.	Borah et al. (2019); Wheelahan & Moodie (2025)

The control group (n = 115) maintained their regular professional development activities, which were systematically documented and monitored. These included weekly departmental meetings (2 hours/week, attendance = 94%); pedagogical training sessions (2 hours/week, engagement = 3.8/5.0); and monthly industry visits (4 hours/month, participation = 88%). To ensure methodological rigour, the control group underwent parallel assessment procedures including identical pretest and post-testing, ongoing teaching performance documentation, standardised classroom observations (κ = .84) and matched professional development evaluation. Cross-condition contamination was prevented through careful scheduling and verified through systematic monitoring (isolation index = .91).

The post-intervention phase (May – June 2024) maintained consistent assessment protocols across both groups. FDDLS Form B was administered under standardised conditions matching the pretest procedures. Comprehensive implementation fidelity metrics were collected to evaluate programme quality, alongside satisfaction surveys that achieved a 95% response rate. This systematic approach to data collection and control group measurement ensured robust evaluation of intervention effects while maintaining high methodological standards.

Ethical consideration and data analysis

The study received Institutional Review Board approval (approval no. LZJGXY-2024096), and all participants were provided written informed consent after being informed of the study's purpose, procedures and right to withdraw. Data were anonymised and handled confidentially. Analyses were conducted using SPSS version 29 for non-parametric tests and baseline equivalence assessment, and Stata 17.0 for regression models and robustness checks, with a two-tailed $\alpha = .05$ and Bonferroni adjustment for multiple comparisons. Diagnostics indicated that the data were not normally distributed (Shapiro–Wilk, $p < .05$); therefore, non-parametric tests were employed for baseline equivalence and group comparisons to ensure valid statistical inference. Pretest homogeneity was confirmed, whereas post-test heterogeneity was observed (Levene's $F = 1.00–1.22$, $p > .05$; $F = 30.12–73.45$, $p < .001$), and no multicollinearity or autocorrelation issues were detected (variance inflation factor < 1.67; Durbin–Watson = 1.92).

Baseline equivalence (RQ1) was assessed using Mann–Whitney *U* tests with effect size $r = Z/\sqrt{N}$. Intervention effects (RQ2) were evaluated using Mann–Whitney *U*, Cohen’s *d* and simple linear regression (Keith, 2019). Demographic influences (RQ3) were examined with Mann–Whitney *U* (gender), Kruskal–Wallis *H* (subject background) and multiple regression with interaction terms (McNeish & Wolf, 2023). Robustness was further assessed using bootstrap re-sampling (1,000 draws), heteroscedasticity-robust standard errors (Collier-Meek et al., 2021; Zeileis et al., 2020) and median regression with quantile modelling (Yang et al., 2024).

Results

Participant profile and baseline equivalence

Of the 230 recruited teachers (115 per group), 24 were excluded due to non-compliance or incomplete data, leaving 206 participants (103 per group; 90% retention). Attrition was balanced across groups (12 per group). Baseline comparisons indicated no significant differences between groups in gender ($\chi^2 = 0.02$, $p = .88$), age ($t(204) = 0.39$, $p = .70$), teaching experience ($t(204) = 0.45$, $p = .66$), subject area ($\chi^2 = 0.04$, $p = .99$) or professional title ($\chi^2 = 0.32$, $p = .96$), confirming demographic comparability (Table 2). Mann–Whitney *U* tests for digital literacy dimensions showed no pre-intervention differences (*p*s = .42–.91, Cohen’s $d = 0.03–0.11$), supporting baseline equivalence (Table 3).

Table 2
Demographic characteristics by group (N = 206)

Characteristics	Experimental group (*n*)	Control group (*n*)	χ^2/t	*p*
Gender			0.02	.88
Male	46 (44.70)	47 (45.60)		
Female	57 (55.30)	56 (54.40)		
Age (years)	38 (7.20)	39 (7.40)	0.39	.70
Teaching experience (years)	12 (6.30)	13 (6.50)	0.45	.66
Subject area			0.04	.99
Science and engineering	27 (26.20)	27 (25.20)		
Business management	28 (27.20)	27 (26.20)		
Arts	24 (23.30)	25 (25.20)		
General education	24 (23.30)	24 (23.30)		
Professional title			0.32	.96
Teaching assistant	18 (17.50)	17 (16.50)		
Lecturer	48 (46.60)	49 (47.60)		
Associate professor	29 (28.20)	28 (27.20)		

Note. Values in parentheses are percentages or *SD*.

Table 3
Mann-Whitney U test results for digital literacy between groups before intervention (N = 206)

Variable	Experimental (*n* = 103)	Control (*n* = 103)	*Z*	*SE*	*p*	95% CI	*r*	Cohen's *d*
DTK	2.92 (0.28)	2.91 (0.31)	-0.11	0.04	.91	[-0.08, 0.07]	.01	0.03
IPCK	2.95 (0.25)	2.93 (0.26)	-0.53	0.04	.60	[-0.08, 0.05]	.04	0.08
DCCK	2.94 (0.29)	2.91 (0.28)	-0.81	0.04	.42	[-0.10, 0.04]	.06	0.11
DTIC	2.86 (0.30)	2.87 (0.31)	0.37	0.04	.71	[-0.07, 0.09]	.03	-0.03
DICC	2.88 (0.32)	2.85 (0.29)	-0.69	0.04	.49	[-0.10, 0.05]	.05	0.10
Total	14.55 (0.64)	14.48 (0.64)	-0.78	0.09	.44	[-0.23, 0.10]	.05	0.11

***p < .001.
Note. Values in parentheses are standard deviations. *r* = effect size ($Z/\sqrt{N}$, *N*=206). Cohen's *d* = $(M_1 - M_2)/\sqrt{[(SD_1^2 + SD_2^2)/2]}$.

Intervention effects

Post-intervention, the experimental group demonstrated significant improvements across all digital literacy dimensions, while the control group remained stable. Total digital literacy increased from *M* = 14.55 (*SD* = 0.64) to *M* = 18.04 (*SD* = 1.95), with a large effect (*r* = .70, *d* = 2.39, $p < .001$). The strongest gains were observed in IPCK (*d* = 1.82, *r* = .68), followed by DCCK (*d* = 1.75, *r* = .66) and DTK (*d* = 1.61, *r* = .62). Mann–Whitney *U* tests confirmed significant group differences across all dimensions (*p*s < .001) (Table 4, Figure 4). Simple linear regression indicated that intervention participation significantly predicted digital literacy outcomes, explaining substantial variance across individual dimensions (R^2 = .55–.59) and total score (R^2 = .68, $p < .001$). The largest effects were observed in IPCK (B = 0.76, 95% CI [0.67, 0.84]), DTK (B = 0.71, 95% CI [0.62, 0.80]) and DTIC (B = 0.70, 95% CI [0.61, 0.78]) (Table 5), indicating that the intervention was highly effective in enhancing teachers' digital literacy across all measured dimensions.

Table 4
Mann-Whitney U test results for digital literacy between groups after intervention (N = 206)

Variable	Experimental (*n* = 103)	Control (*n* = 103)	*Z*	*SE*	*p*	95% CI	*r*	Cohen's *d*
DTK	3.63 (0.55)	2.92 (0.31)	-8.86	0.06	***	[-0.83, -0.60]	.62	1.61
IPCK	3.71 (0.53)	2.93 (0.26)	-9.78	0.06	***	[-0.88, -0.67]	.68	1.82
DCCK	3.61 (0.49)	2.91 (0.28)	-9.45	0.06	***	[-0.80, -0.60]	.66	1.75
DTIC	3.56 (0.58)	2.88 (0.31)	-8.38	0.07	***	[-0.80, -0.56]	.58	1.47
DICC	3.55 (0.55)	2.85 (0.29)	-8.76	0.06	***	[-0.81, -0.59]	.61	1.56
Total	18.04 (1.95)	14.50 (0.64)	-10.06	0.20	***	[-3.94, -3.18]	.70	2.39

Note. Same conventions as Table 3.

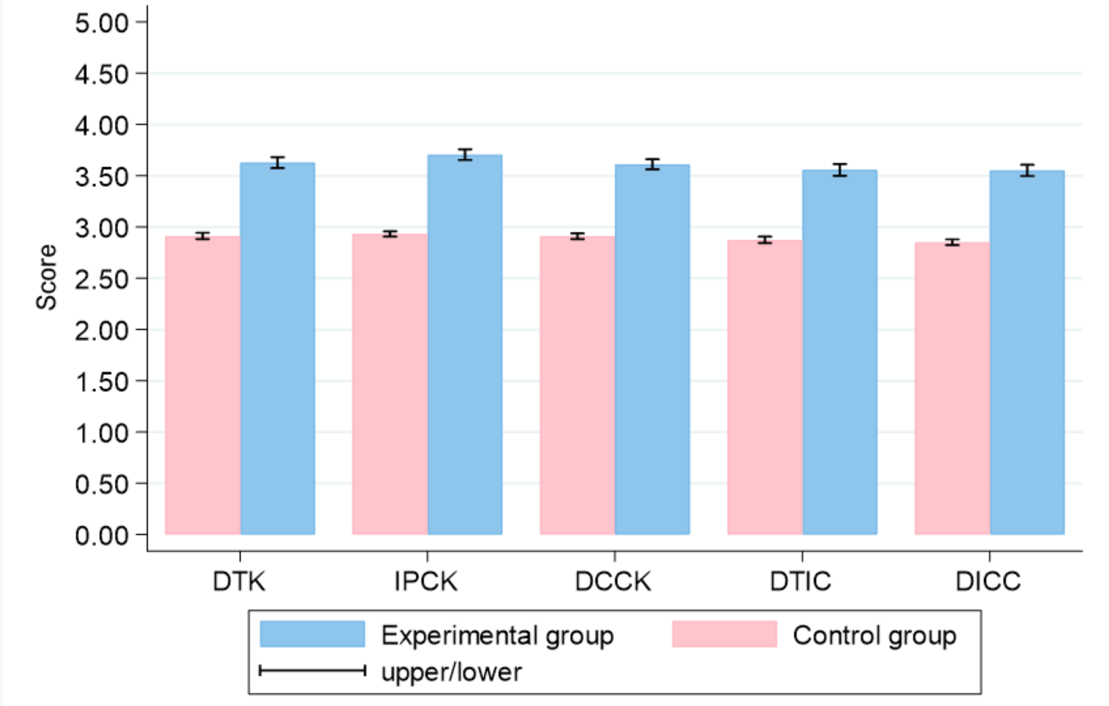

Figure 4. Comparison of digital literacy dimensions between groups after intervention
Note. Error bars represent ±1 *SE*.

Table 5
Simple regression analysis of digital literacy (N = 206)

Variable	DTK	IPCK	DCCK	DTIC	DICC	Total
EG	0.71 (0.04)***	0.76 (0.04)***	0.67 (0.04)***	0.70 (0.04)***	0.67 (0.04)***	3.50 (0.17)***
95% CI	[0.62, 0.80]	[0.67, 0.84]	[0.59, 0.75]	[0.61, 0.78]	[0.59, 0.75]	[3.17, 3.84]
Constant	-0.00 (0.03)	-0.00 (0.03)	0.00 (0.03)	-0.00 (0.03)	0.00 (0.03)	-0.00 (0.12)
95% CI	[-0.06,0.06]	[-0.06,0.06]	[-0.06, 0.06]	[-0.06, 0.06]	[-0.06, 0.06]	[-0.24, 0.23]
R^2	0.56	0.59	0.55	0.56	0.56	0.68
F	260.17***	293.75***	253.54***	256.17***	262.28***	429.00***

***$p < .001$.
Note. EG = experimental group. Values in parentheses are standard errors. Coefficients are unstandardised (B).

Demographic influences and controlled regression analyses

Pre-intervention analyses indicated that male teachers consistently outperformed female teachers across all digital literacy dimensions (r = .14–.51), and teachers from science, engineering and business management disciplines scored higher than those from arts and general education (η^2 = .03–.37) (Tables

6 and 7). Following the 10-week intervention, these gaps were reduced within the experimental group (r = .10–.23 for gender; η^2 = .029–.133 for subject area) (Tables 8 and 9), suggesting that the programme effectively narrowed pre-existing disparities in digital literacy.

Table 6
Mann-Whitney U test results for digital literacy across gender before intervention (N = 206)

Variable	Male (n = 94)	Female (n = 112)	Rank sum	z	r	95% CI
DTK	3.02 (2.81–3.26)	2.83 (2.62–3.07)	11204.0/10117.0	3.46***	.24	[0.11, 0.37]
IPCK	3.00 (2.76–3.21)	2.87 (2.68–3.11)	10780.0/10541.0	2.47*	.17	[0.04, 0.30]
DCCK	3.04 (2.76–3.20)	2.87 (2.65–3.13)	10604.0/10717.0	2.05*	.14	[0.01, 0.27]
DTIC	3.01 (2.66–3.19)	2.77 (2.53–3.06)	11146.0/10175.0	3.33***	.23	[0.10, 0.36]
DICC	2.99 (2.76–3.23)	2.70 (2.54–3.03)	11657.0/9664.0	4.52***	.32	[0.19, 0.44]
Total	14.93 (14.37–15.28)	14.22 (13.85–14.59)	12877.0/8444.0	7.39***	.51	[0.40, 0.61]

*p < .05. ***p < .001.
Note. Interquartile ranges in parentheses.

Table 7
Kruskal-Wallis H test results for digital literacy across subject areas before intervention (N = 206)

Variable	1 (n = 54)	2 (n = 55)	3 (n = 49)	4 (n = 48)	$\chi^2(3)$	η^2	95% CI	Post-hoc (Z)
DTK	111.69	136.00	77.78	83.31	32.00***	.14	[.08, .21]	2 > 1 (3.24**), 1 > 3 (2.89**), 1 > 4 (2.76**)
IPCK	115.04	119.71	77.76	98.23	15.60**	.06	[.02, .12]	1 > 3 (3.12**), 2 > 3 (3.45**), 2 > 4 (2.68*)
DCCK	126.94	117.36	78.08	87.19	23.83***	.10	[.05, .17]	1 > 3 (3.56***), 1 > 4 (3.12**), 2 > 3 (2.89**)
DTIC	116.96	110.96	95.84	87.63	7.83*	.03	[.00, .08]	1 > 4 (2.45*)
DICC	113.09	118.00	92.00	87.88	9.76*	.04	[.01, .09]	1 > 4 (2.56*), 2 > 4 (2.78**)
Total	134.28	141.93	60.22	69.02	79.13***	.37	[.28, .45]	1 > 3 (4.12***), 1 > 4 (3.89***), 2 > 3 (4.23***)

*p < .05. **p < .01. ***p < .001.
Note. Mean ranks reported. 1 = science and engineering; 2 = business management; 3 = arts; 4 = general education. ">" indicates significantly higher (p < .05). η^2 = effect size.

Table 8
Mann-Whitney U test results for digital literacy across gender in experimental group after intervention (n = 103)

Variable	Male	Female	Rank sum	*z*	*r*	95% CI
DTK	3.83 (3.52–4.14)	3.60 (3.19–4.01)	2718.0/2638.0	2.16*	.15	[0.02, 0.28]
IPCK	3.81 (3.49–4.13)	3.64 (3.31–3.97)	2705.0/2651.0	2.08*	.14	[0.01, 0.27]
DCCK	3.74 (3.41–4.07)	3.54 (3.12–3.96)	2612.0/2744.0	1.46	.10	[-0.03, 0.23]
DTIC	3.83 (3.48–4.18)	3.46 (3.06–3.86)	2725.0/2631.0	2.21*	.15	[0.02, 0.28]
DICC	3.76 (3.44–4.08)	3.45 (3.02–3.88)	2870.0/2486.0	3.17***	.22	[0.09, 0.35]
Total	18.99 (18.28–19.70)	18.11 (16.88–19.34)	2898.0/2458.0	3.36***	.23	[0.10, 0.36]

Note. Same conventions as Table 6. Sample sizes: male (*n* = 46), female (*n* = 57).

Table 9
Kruskal-Wallis H test results for digital literacy across subject areas in experimental group after intervention (n = 103)

Variable	1 (*n* = 27)	2 (*n* = 28)	3 (*n* = 24)	4 (*n* = 24)	χ^2 (3)	η^2	95% CI	Post-hoc (*Z*)
DTK	54.48	66.68	40.58	43.50	12.39 **	.095	[.03, .16]	2 > 3 (3.23**), 2 > 4 (2.66**)
IPCK	50.00	63.71	41.04	51.54	7.66	.078	[.01, .14]	2 > 3 (3.12**), 2 > 4 (2.68*)
DCCK	59.44	53.36	42.75	51.29	4.05	.040	[.00, .09]	1 > 3 (2.89*)
DTIC	56.19	61.39	46.88	41.46	6.99	.071	[.00, .13]	2 > 4 (2.56*)
DICC	54.78	57.96	48.88	45.04	2.91	.029	[.00, .08]	2 > 4 (2.45*)
Total	58.74	66.32	37.00	42.71	16.18 **	.133	[.05, .19]	2 > 3 (3.23**), 2 > 4 (2.66**)

Note. Same conventions as Table 7. Sample sizes per group indicated in columns.

Multiple regression analyses controlling for gender and subject background confirmed that the intervention remained the strongest predictor of digital literacy outcomes across all dimensions (B = 0.67–0.76, R^2 = .56–.60; total score R^2 = .68, $p < .001$) (Table 10). Interaction models showed that moderation by gender and subject area was limited; although a few interaction terms reached significance (e.g., intervention × business background for IPCK, B = –0.13; intervention × female for DICC, B = –0.14), their effect sizes were small relative to the main intervention effects (Table 11), indicating that the intervention was broadly effective regardless of teachers' demographic characteristics.

Table 10
Multiple regression analysis results for digital literacy (N = 206)

Variable	DTK	IPCK	DCCK	DTIC	DICC	Total
EG	0.71 (0.04)***	0.76 (0.04)***	0.67 (0.04)***	0.70 (0.04)***	0.67 (0.04)***	3.51 (0.17)***
95% CI	[0.63, 0.79]	[0.68, 0.84]	[0.59, 0.75]	[0.62, 0.78]	[0.59, 0.75]	[3.17, 3.85]
Female	-0.03 (0.05)	-0.05 (0.05)	-0.03 (0.05)	-0.03 (0.05)	-0.07 (0.04)	-0.22 (0.18)
95% CI	[-0.13,0.07]	[-0.15, 0.05]	[-0.13,0.07]	[-0.13, 0.07]	[-0.15,0.01]	[-0.57,0.13]
Business management	0.01 (0.06)	0.11 (0.06)	0.02 (0.06)	0.03 (0.06)	0.01 (0.06)	0.18 (0.23)
95% CI	[-0.11,0.13]	[-0.01,0.23]	[-0.10,0.14]	[-0.09,0.15]	[-0.11,0.13]	[-0.27,0.63]
Arts	-0.05 (0.07)	0.04 (0.07)	0.03 (0.06)	-0.04 (0.06)	0.04 (0.06)	0.01 (0.25)
95% CI	[-0.19,0.09]	[-0.10,0.18]	[-0.09,0.15]	[-0.16, 0.08]	[-0.08,0.16]	[-0.48, 0.50]
General education	-0.04 (0.06)	0.07 (0.06)	0.05 (0.06)	-0.09 (0.06)	-0.04 (0.06)	-0.04 (0.25)
95% CI	[-0.16,0.08]	[-0.05,0.19]	[-0.07, 0.17]	[-0.21, 0.03]	[-0.16,0.08]	[-0.53, 0.45]
Constant	0.03 (0.05)	-0.03 (0.05)	0.00 (0.05)	0.04 (0.05)	0.03 (0.05)	0.08 (0.20)
95% CI	[-0.07,0.13]	[-0.13,0.07]	[-0.10, 0.09]	[-0.06, 0.14]	[-0.06,0.13]	[-0.31, 0.47]
R^2	0.57	0.60	0.56	0.57	0.57	0.68
F	52.09***	60.21***	50.14***	52.68***	53.25***	86.11***

Note. Same conventions as Table 5; additional variables included as controls (female, business management, arts, general education). Reference groups: male, science and engineering. EG = experimental group.

Table 11
Multiple regression results of digital literacy with subject and gender intervention effects (N = 206)

Variable	DTK	IPCK	DCCK	DTIC	DICC	Total
EG	0.78 (0.09)***	0.71 (0.09)***	0.67 (0.09)***	0.80 (0.09)***	0.75 (0.09)***	3.70 (0.36)***
95% CI	[0.60, 0.97]	[0.52, 0.89]	[0.49, 0.84]	[0.62, 0.98]	[0.57, 0.92]	[2.99, 4.41]
Exp×Bus.	-0.11 (0.10)	-0.13 (0.10)	-0.09 (0.09)	-0.12 (0.09)	-0.10 (0.09)	-0.55 (0.37)
95% CI	[-0.31, 0.09]	[-0.33, 0.07]	[-0.27, 0.09]	[-0.30, 0.06]	[-0.28, 0.08]	[-1.28, 0.18]
Exp×Arts	-0.09 (0.10)	-0.11 (0.10)	-0.08 (0.09)	-0.10 (0.09)	-0.09 (0.09)	-0.47 (0.37)
95% CI	[-0.29, 0.11]	[-0.31, 0.09]	[-0.26, 0.10]	[-0.28, 0.08]	[-0.27, 0.09]	[-1.20, 0.26]
Exp×GE	-0.08 (0.10)	-0.09 (0.10)	-0.07 (0.09)	-0.09 (0.09)	-0.08 (0.09)	-0.41 (0.37)
95% CI	[-0.28, 0.12]	[-0.29, 0.11]	[-0.25, 0.11]	[-0.27, 0.09]	[-0.26, 0.10]	[-1.14, 0.32]
Exp×Fem	-0.07 (0.10)	-0.10 (0.10)	-0.07 (0.09)	-0.08 (0.09)	-0.14 (0.09)	-0.45 (0.37)
95% CI	[-0.25, 0.12]	[-0.29, 0.09]	[-0.25, 0.12]	[-0.27, 0.10]	[-0.32, 0.04]	[-1.18, 0.28]
Constant	3.21 (0.08)***	3.15 (0.08)***	3.18 (0.08)***	3.22 (0.08)***	3.19 (0.08)***	15.95 (0.32)***
95% CI	[3.05, 3.37]	[2.99, 3.31]	[3.02, 3.34]	[3.06, 3.38]	[3.03, 3.35]	[15.32,16.58]
R^2	0.57	0.61	0.56	0.58	0.58	0.69
F	29.00	34.23	27.49	30.23	30.19	48.08

***$p < .001$.
Note. Values in parentheses are standard errors. EG = experimental group. Exp×Bus = experimental group × Business. Exp×Arts = experimental group × arts. Exp×GE = experimental group × general education. Exp×Fem = Experimental group × Female. Reference groups: male, science and engineering.

Robustness check results

Robustness of the intervention effects was verified using bootstrap re-sampling (1,000 replications), Huber-White heteroskedasticity-robust standard errors, and median regression. The intervention remained highly significant across all digital literacy dimensions ($p < .001$), with the largest effects observed for IPCK (B = 0.76–0.85), followed by DTK (B = 0.71–0.77) and DTIC (B = 0.70–0.75). Control variables exhibited minimal influence (B = –0.07 to 0.11), and model fit indices were consistent across methods (R^2 = 0.48–0.68; χ^2 = 273–1968; F = 54–103, p < .001), confirming the robustness and stability of the intervention outcomes (Table 12).

Table 12
Results of robustness checks (N = 206)

Variable	Bootstrap	Robust *SE*	Median regression
Panel A: Treatment effects			
DTK	0.71 (0.04)***	0.71 (0.04)***	0.77 (0.03)***
IPCK	0.76 (0.04)***	0.76 (0.04)***	0.85 (0.04)***
DCCK	0.67 (0.04)***	0.67 (0.04)***	0.74 (0.04)***
DTIC	0.70 (0.04)***	0.70 (0.04)***	0.75 (0.05)***
DICC	0.67 (0.04)***	0.67 (0.04)***	0.74 (0.04)***
Total	3.51 (0.17)***	3.51 (0.17)***	4.07 (0.09)***
Panel B: Control variables			
Variable	Bootstrap	Robust *SE*	Median regression
Female	-0.03 to -0.07	-0.03 to -0.07	0.00 to -0.01
Business management	0.01 to 0.11	0.01 to 0.11	0.00 to 0.02
Arts	-0.05 to 0.04	-0.05 to 0.04	0.00 to 0.01
General education	-0.09 to 0.07	-0.09 to 0.07	-0.01 to 0.01
Panel C: Model fit			
Measure	Bootstrap	Robust *SE*	Median regression
R^2	.56 to .68	.57 to .68	.48 to .66
Model test	χ^2 = 273-509***	F = 54-103***	χ^2 = 489-1968***

****p* < .001.
Note. Values in parentheses are standard errors. Reference groups: male, science and engineering. Coefficients are unstandardised (B). Panel A reports coefficient estimates. Panel B reports ranges of coefficient estimates across dimensions. Panel C reports model fit measures. Bootstrap = 1,000 replications. Robust SE = Huber-White heteroskedasticity-robust standard errors.

Discussion

Differential effects and demographic nuances in digital literacy development

The intervention yielded exceptional gains across all digital literacy dimensions (d = 1.47–1.82), far surpassing Cohen's (2013) benchmark for large effects and affirming both its effectiveness and demographic relevance. Such impact reflects the systematic integration of TPACK with industry frameworks, the intensive 10-week intervention format and a dimension-specific progression design. Effect magnitude varied, revealing distinct developmental trajectories. The largest improvement in IPCK (d = 1.82) underscores strengthened alignment between pedagogy and industry practice, consistent with Yuniarti et al. (2024). DCCK also improved markedly (d = 1.75), reflecting enhanced capacity to adapt content to evolving technological demands, echoing Al-Adwan et al. (2024). Strong gains in DTK (d = 1.61) highlight reinforced technological foundations essential for digital teaching. However, the relatively smaller improvements in DICC (d = 1.47) and DTIC (d = 1.56) warrant critical examination. These dimensions, focusing on collaborative and innovative teaching skills, showed limited gains possibly due to their complexity requiring sustained stakeholder engagement and systemic support.

The insignificant findings in these areas suggest potential barriers in developing higher-order digital competencies, highlighting the need for extended intervention periods and enhanced institutional support mechanisms. Demographic analyses further reinforced intervention effectiveness while revealing persistent patterns. Pre-intervention gender gaps (r = .51) narrowed post-intervention (rs = .14–.23), with business management teachers showing stronger performance in DTK (η^2 = .095). Overall, these findings validate both the effectiveness of the integrated framework and its adaptability across different demographic groups, while highlighting areas requiring enhanced support for optimal outcomes.

Theoretical contributions

This study advances educational technology research by elucidating digital literacy development in vocational settings across conceptual, methodological, and contextual dimensions. First, this study advances educational technology research by developing and validating an innovative framework that integrates TPACK with industry–education principles (Gong, 2024; Mishra & Koehler, 2006), extending technology integration theories to vocational contexts through systematic incorporation of workplace demands. Its four-layer structure aligns TPACK components with industry requirements while incorporating teacher characteristics as moderating variables, providing a comprehensive lens to examine how individual differences shape digital literacy development in professional settings.

Second, the study reveals temporal dynamics in competence evolution through a longitudinal design, establishes causal relationships via a quasi-experimental approach and identifies complex interaction patterns between institutional arrangements, organisational culture and individual development using systematic quantitative analysis. Third, it contextualises digital literacy within vocational education, showing how competencies evolve in specific institutional and cultural contexts and illustrating how institutional characteristics and industry requirements shape development, thus contributing nuanced insights to educational technology theory.

Practical significance

Building on theoretical insights, this study offers actionable contributions to vocational education via framework implementation, professional development and localised strategies. For framework implementation, it equips institutions with a four-layer integrated evaluation system including five primary indicators for assessing teachers' digital literacy, such as using digital tools for industry simulation and creating digital teaching resources. Differentiated benchmarks allow engineering teachers to focus on virtual lab integration and business teachers on digital marketing tools.

For professional development, it provides guidelines for modular training, enabling teachers to first master basic digital tools (e.g., learning management systems) before progressing to industry-specific applications. The intervention further recommends pairing teachers with industry mentors and organising technology-sharing workshops to support sustainable skill development. Regarding localised strategies, the study offers solutions for Chinese vocational contexts, including integrating widely used platforms (e.g., DingTalk, Chaoxing Xuexitong) into teaching, promoting interactive and collaborative learning and fostering sustained industry-education collaboration through digital practice bases, virtual industry visits and other technology-enabled initiatives.

Cross-context transferability and implementation considerations

The intervention's modular design and staged progression indicate potential transferability across diverse vocational education systems, though implementation pathways will vary. Three contextual dimensions shape adaptation. First, institutional arrangements mediate transferability. In dual-system contexts (e.g., Germany), where industry partnerships are institutionalised, IPCK and DICC modules can be intensified through existing collaborative networks (McGrath & Yamada, 2023; Wheelahan & Moodie, 2025). In school-based systems (e.g., Australia), DTK and DTIC components may be prioritised to build campus-centred digital innovation (McGrath & Yamada, 2023; Wheelahan & Moodie, 2025). The 10-week structure allows both concentrated delivery in dual systems and extended formats in school-based contexts.

Second, digital maturity levels influence progression. Advanced economies may move rapidly beyond DTK to focus on DTIC and DICC, whereas emerging economies might extend DTK and DCCK to consolidate digital foundations before advancing to integration. The substantial improvements observed across all dimensions suggest sufficient intervention intensity to support these differentiated trajectories. Third, resource availability determines feasibility. While our implementation leveraged advanced infrastructure, core elements can be delivered via basic platforms. The strong improvements in digital teaching knowledge indicate that resource-constrained contexts can still achieve meaningful outcomes through selective adaptation and localised technology use. Preliminary collaborations in South-east Asia suggest feasibility, with local adaptation focusing on DTK and IPCK while maintaining fidelity to core principles. Overall, the framework demonstrates adaptability across contexts while preserving effectiveness, provided that institutional, developmental and resource contingencies are systematically addressed.

Conclusion and future directions

Against the backdrop of vocational education's digital transformation and the persistent gaps in theoretical integration, empirical validation and contextual implementation guidance, this study developed and validated an integrated theoretical framework for enhancing vocational teachers' digital literacy through a systematic intervention grounded in TPACK and industry-education integration principles. Using a rigorous quasi-experimental pretest–post-test matched-group design, the study addressed three research questions. Baseline analyses confirmed equivalence across all dimensions, establishing a robust foundation for evaluation. The 10-week intervention substantially improved all dimensions, particularly IPCK and DCCK, demonstrating effectiveness in developing both foundational and integrative competencies. Regression analyses indicated that effects persisted after controlling for demographic factors, though with notable interaction effects between intervention and teacher characteristics. Building on these findings, this study offers three layers of contribution. Theoretically, this study advances educational technology theory by enriching TPACK framework's application in vocational education contexts, establishing longitudinal methodological foundations and enhancing contextual understanding of technology integration. Practically, it provides evaluation tools, modular training approaches and localised strategies. Internationally, the framework demonstrates transferability across institutional arrangements, digital maturity levels and resource conditions.

Despite these contributions, some limitations warrant consideration. First, although the quasi-experimental design with a control group strengthens internal validity, the 10-week intervention may be insufficient for developing complex competencies such as DICC and DTIC, which require sustained practice and systemic support. Second, while quantitative measures revealed significant effects, the absence of qualitative data limits understanding of how teachers integrate digital competencies into practice and the barriers they encounter. Third, while the framework demonstrates effectiveness in the Chinese vocational education context, its validation in other vocational educational contexts remains to be examined. Future research could employ longer interventions to track competency development trajectories more comprehensively. Mixed-methods approaches would provide deeper insights into developmental processes and contextual factors influencing different competency dimensions. Cross-context validation studies could assess the framework's adaptability and culture-specific requirements. Finally, examining institutional support mechanisms and designing targeted strategies for enhancing collaborative and innovative teaching competencies would strengthen the framework's practical utility.

Overall, this study presents an empirically grounded and theoretically integrative framework for enhancing vocational teachers' digital literacy by bridging TPACK with industry–education integration principles. The findings demonstrate how structured, modular professional development can support differentiated competence growth within digitally transforming vocational systems. By situating teacher digital literacy at the intersection of pedagogy, industry relevance and institutional context, this study offers a scalable reference for future research and policy-oriented teacher development.

Author contributions

Huili Cui: Conceptualisation, Methodology, Data curation, Formal analysis, Investigation, Validation, Project administration, Software, Supervision, Visualisation, Writing – original draft, Writing – review and editing; **Hao Dong:** Data collection, Writing – review and editing; **Mambetakunov Ulanbek:** Writing – review and editing.

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