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Digital Pedagogical Competencies: A Professional Development Framework for Adaptive Differentiated Instruction in Mathematics Education

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Abstract. This study developed, implemented, and evaluated an integrated digital pedagogical competency (IDPC) framework designed to equip mathematics teachers in Jambi City, Indonesia, with digital pedagogical competencies for implementing adaptive differentiated learning. Using a convergent mixed-methods quasi-experimental design with a non-equivalent control group pre-test–post-test framework, 60 junior high school mathematics teachers (30 experimental, 30 control) participated in an 18-session, 54-contact-hour professional development (PD) program integrating technological pedagogical content knowledge (TPACK) and digital competence of educators (DigCompEdu) frameworks through professional learning communities (PLCs), coaching, and practice-based learning. Data were collected using a validated TPACK questionnaire ($\alpha = 0.84 - 0.91$) and the observation protocol for differentiated instruction (OPDI; $\kappa = 0.78 - 0.85$), supplemented by interviews and document analysis. Results revealed

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significant improvements in the experimental group across all TPACK dimensions, with the largest gains in integrative TPACK (d = 2.15) and TPK (d = 2.11). ANCOVA confirmed significant between-group post-test differences across all dimensions (partial η^2 = 0.20–0.73). Classroom observations showed dramatic improvements in differentiated practices (d = 3.38). Qualitative thematic analysis identified five themes: transformative mindset shifts, enhanced technological confidence, improved differentiation practices, sustained collaborative learning through professional learning communities (PLCs), and persistent implementation challenges. Self-reported data and the quasi-experimental design limit causal claims. The IDPC framework offers an empirically validated, replicable model demonstrating how systematic integration of digital pedagogy and adaptive learning can transform teacher competencies in mathematics education.

Keywords: digital pedagogical competence; adaptive differentiated learning; mathematics education; TPACK; DigCompEdu; teacher training; quality education; professional learning communities; instructional coaching

1. Introduction

Digital transformation has fundamentally reshaped the educational landscape, creating new paradigms for learning design and delivery (Bajac & Fišer, 2024; Bonfield et al., 2020; Mohamed Hashim et al., 2022). In mathematics education, this shift demands that teachers move beyond content mastery and traditional pedagogy to integrate technology effectively for personalized, adaptive learning (Coles & Helliwell, 2023; Engelbrecht et al., 2020; Fitriana et al., 2025; Hendriyanto et al., 2024; Hoyles, 2018; Kholid et al., 2023; Muhaimin et al., 2025). Adaptive differentiated learning, which involves tailoring content and processes to individual readiness and interests (Gheyssens et al., 2022; NCTM, 2000), has become a recognized pedagogical standard shown to improve achievement and higher-order thinking (Herliana et al., 2024; Hidayati et al., 2025).

However, implementing this approach in large, diverse classrooms requires digital tools such as adaptive learning systems and formative assessment platforms (Hendriyanto et al., 2024; Okafor, 2025; Pahmi et al., 2023). This potential requires adequate digital pedagogical competencies, defined by two influential frameworks: technological pedagogical content knowledge (TPACK) (Mishra & Koehler, 2006) and the digital competence framework for educators (DigCompEdu) (Redecker & Punie, 2017). TPACK emphasizes the holistic integration of content, pedagogical, and technological knowledge (Angeli & Giannakos, 2019; Herring et al., 2006; Zhang & Yie, 2026), while DigCompEdu outlines 22 competencies across six areas, with research indicating that teachers often remain at early stages in digital content creation and assessment (García-Vandewalle García et al., 2023; Voogt et al., 2015).

Despite these frameworks, a significant competency gap persists. Studies in Indonesia and elsewhere reveal limited digital competencies among mathematics teachers (Fitriana et al., 2025; Ghomi & Redecker, 2019; Mailizar & Johar, 2021). In Indonesia, only 23% of teachers reported confidence in using technology for differentiated learning (Pusat Asesmen dan Pembelajaran, 2021). A preliminary study in Jambi City found that while 78% of teachers have device access, fewer than 20% implement technology-supported differentiation. This gap stems partly from professional development (PD) programs that are sporadic, technically focused, and rely on ineffective one-off workshops (Avalos, 2011; Darling-Hammond, 2017; Kennedy, 2016).

This study addresses several research gaps. First, no existing PD framework systematically integrates TPACK and DigCompEdu with a specific focus on adaptive differentiated mathematics learning. Out of 186 reviewed articles, only eight explicitly linked digital competencies with differentiation, and none developed a comprehensive PD framework for mathematics teachers. Second, empirical research measuring PD effectiveness through quasi-experimental designs remains scarce (Bate, 2010; Dede et al., 2008). Third, mechanisms through which teachers transform digital knowledge into practice are underexplored (Desimone, 2009). Fourth, middle-income contexts such as those of Indonesia are underrepresented (Hennessy et al., 2010; Opfer & Pedder, 2011).

The urgency of this research is driven by Indonesia's "Independent Curriculum," which prioritizes differentiated learning and technology integration (Pusat Kurikulum dan Pembelajaran, 2022). The novelty lies in developing an integrative PD framework combining TPACK and DigCompEdu with practice-based models (professional learning communities [PLCs], coaching, mentoring), aligning with evidence that job-embedded PD produces larger effect sizes ($d = 0.89$) than traditional workshops ($d = 0.24$) (Kraft et al., 2018; Yoon et al., 2007).

This study aims to develop, implement, and evaluate an integrated digital pedagogical competency (IDPC) framework to strengthen junior high school mathematics teachers' digital pedagogical competencies for adaptive differentiated learning. Through a mixed-methods quasi-experimental design, it measures the framework's effectiveness while exploring teachers' experiences and enabling factors for scalability within the Indonesian education system.

1.1 Research Questions

To address the research gap regarding the integration of digital tools in tailored mathematics instruction, this study is guided by the following four research questions:

1. RQ1: To what extent does participation in the IDPC-based PD program improve mathematics teachers' digital pedagogical competencies (TPACK dimensions)?
2. RQ2: How do the experimental and control groups differ in post-test digital pedagogical competencies after controlling baseline scores?
3. RQ3: What changes occur in teachers' differentiated instruction practices as measured by classroom observations?

4. RQ4: What are the mechanisms, enabling factors, and challenges experienced by teachers during the PD program?

2. Literature Review

Research on digital pedagogical competencies in mathematics education has grown substantially in the past decade. TPACK-based studies have demonstrated that mathematics teachers' technological integration varies significantly by experience, technology type, and mathematical topic (Bowers & Stephens, 2011). Teachers with extensive experience tend to have strong pedagogical content knowledge (PCK) but weaker technological content knowledge (TCK) and technological pedagogical knowledge (TPK), while novice teachers show higher technological knowledge (TK) but struggle with integration. Importantly, TPACK development follows iterative rather than linear trajectories (Voogt et al., 2015). Despite these insights, TPACK has been critiqued for the difficulty of measuring its constructs independently and for the ambiguity of boundaries between knowledge domains (Angeli & Valanides, 2020).

The DigCompEdu framework complements TPACK by providing a practice-oriented competency map. Validation studies involving over 10,000 teachers across 15 European countries showed that the majority remained at A2–B1 proficiency levels, with particular weaknesses in empowering learners and facilitating digital competence (Ghomi & Redecker, 2019). However, most DigCompEdu research focuses on European contexts, leaving gaps in understanding its applicability to diverse educational settings.

Studies on differentiated learning in mathematics have shown encouraging results. A meta-analysis by Deunk et al. (2018) found an average effect size of $d = 0.54$, with technology-supported differentiation yielding larger effects ($d = 0.67$) than manual approaches ($d = 0.42$). Prast et al. (2018) demonstrated benefits across ability levels. However, implementation faces challenges including classroom management complexity, teacher workload, and technology competency gaps (Smale-Jacobse et al., 2019).

Professional development literature identifies sustained, content-focused, and collaborative PD as most being effective (Desimone & Pak, 2017). PLCs show positive correlations with practice changes ($r = 0.37$) and student achievement ($r = 0.23$) (Lomos et al., 2011). Coaching produces medium effects on teaching practice ($d = 0.49$) (Kraft et al., 2018). Yet, few PD programs integrate TPACK and DigCompEdu with differentiation-specific strategies, while fewer employ rigorous quasi-experimental evaluation designs.

3. Theoretical Framework

3.1 TPACK and DigCompEdu Integration

This study integrates two complementary frameworks. TPACK (Mishra & Koehler, 2006), building on Shulman (1986) PCK, conceptualizes effective technology integration through seven interrelated knowledge constructs: Content knowledge (CK), pedagogical knowledge (PK), technological knowledge (TK), and their intersections: PCK, TCK, TPK, and the integrative TPACK (Figure 1).

DigCompEdu (Redecker & Punie, 2017) provides an operational framework of 22 competencies across six areas with progressive proficiency levels (A1–C2). In this study, TPACK serves as the conceptual foundation, while DigCompEdu identifies specific practices, with particular focus on Area 3 (Teaching and Learning) and Area 5 (Empowering Learners).

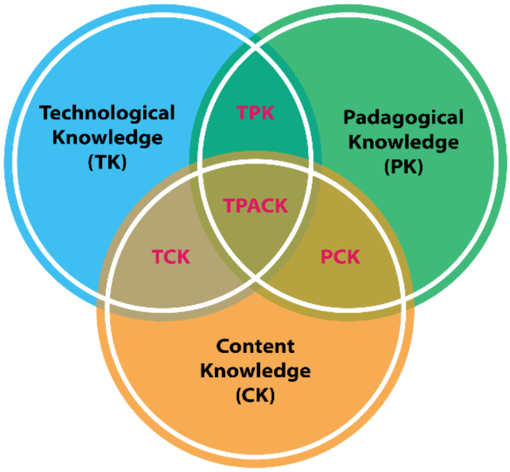

Figure 1: TPACK framework

Adaptive differentiated learning integrates Tomlinson's (2001) differentiation philosophy by modifying content, process, product, and learning environment based on student readiness through adaptive technology that adjusts learning in real-time (VanLehn, 2011). In mathematics, this approach is particularly relevant given the subject’s hierarchical nature and the wide variation in learning pace among students.

3.2 The IDPC Framework

Based on the theoretical synthesis, this study develops the integrated digital pedagogical competency (IDPC) framework (Figure 2), built on three pillars: (a) integrated competencies, unifying TPACK and DigCompEdu for adaptive differentiation; (b) collaborative and situational learning, positioning PD as a social process within PLCs reinforced by coaching; and (c) iterative design–implementation–reflection cycles, driving competency internalization through repeated practice-based learning.

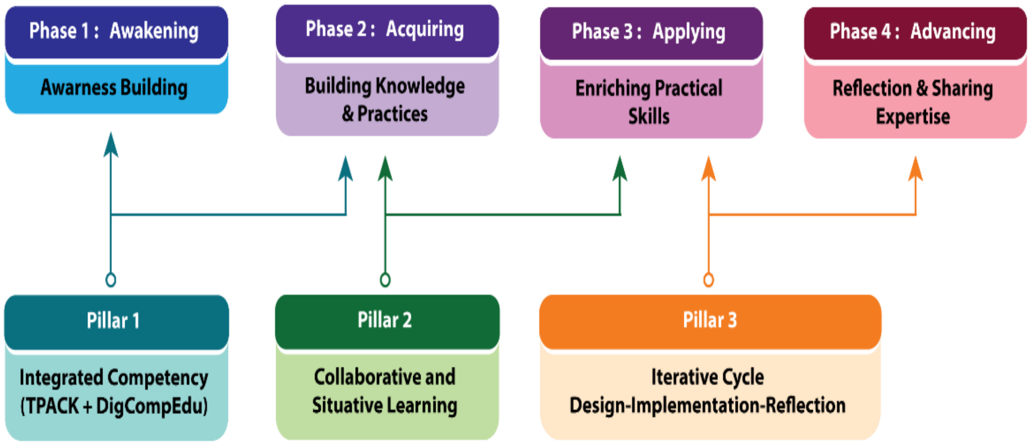

Figure 2: Integrated digital pedagogical competency (IDPC) framework

The framework operates through four progressive phases: Awakening (building awareness of student diversity and technology's role), Acquiring (developing foundational TK, PK, and CK through workshops and micro-teaching), Applying (authentic classroom implementation with coaching support), and Advancing (reflection, showcase, and continuous improvement planning).

3.3 Conceptual Model and Research Hypotheses

The conceptual model (Figure 3) hypothesizes that IDPC-based PD strengthens TPK as a proximal mechanism, which develops into integrative TPACK through content-specific enactment cycles, ultimately improving differentiated instruction practice (OPDI). Table 1 maps the analytical translation of IDPC elements to research variables and instruments.

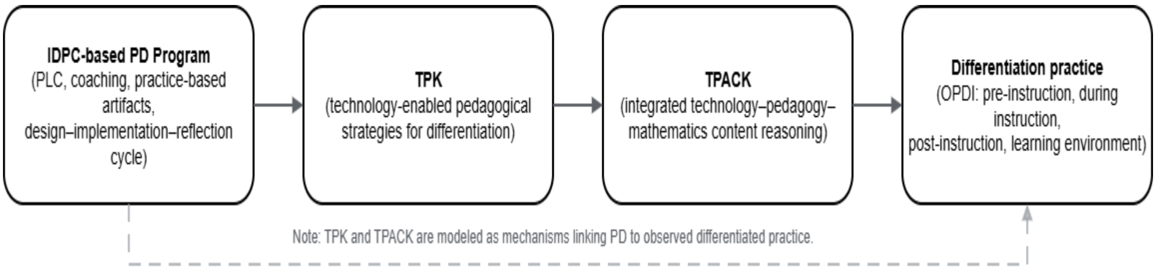

Figure 3: Conceptual model linking IDPC-based professional development to differentiated instruction practice through TPK and TPACK

Based on this framework, four hypotheses were proposed: (H1) significant pre-to-post improvements in all TPACK dimensions; (H2) significantly higher post-test TPACK scores for the experimental group; (H3) greater improvements in differentiated teaching practices; and (H4) the largest gains in TPK and integrative TPACK, as these are least addressed in traditional PD.

Table 1: Analytical translation of the IDPC framework into research variables and measures

IDPC element (intervention logic)	Construct in the conceptual model	Research variable in this study	Instrument and indicator
IDPC-based PD program delivered through PLC, coaching, practice-based artifacts, and iterative design–implementation–reflection cycles	PD exposure as causal input	Group membership and PD participation (experimental vs control), with participation intensity described (attendance, coaching completion)	Program records, attendance logs
Technology-enabled pedagogy for differentiation	TPK as proximal mechanism	TPK score change and post-test adjusted TPK	TPACK questionnaire, TPK subscale (pre- and post-)
Integrated technology–pedagogy–mathematics content reasoning	TPACK as integrative mechanism	TPACK score change and post-test adjusted TPACK	TPACK questionnaire, TPACK subscale (pre- and post-)
Enactment of differentiated instruction in classrooms	Differentiation practice outcome	OPDI baseline to endline change and endline comparison with control	OPDI observation rubric: pre-instruction, during instruction, post-instruction, learning environment, total score

4. Methodology

4.1 Research Design

This study employed a convergent mixed-methods design within a quasi-experimental non-equivalent control group pre-test–post-test framework. Quantitative and qualitative data were collected concurrently during the implementation period and analyzed separately before being integrated at the interpretation stage through joint displays (Creswell & Plano Clark, 2018). The quantitative strand estimated the PD program's impact on TPACK competencies and observed differentiation practices, while the qualitative strand examined teachers' experiences and change mechanisms through thematic inquiry.

4.2 Participants and Settings

Sixty junior high school mathematics teachers from 10 public schools in Jambi City, Indonesia were selected through purposive sampling based on the following criteria: actively teaching grades VII–IX, at least two years of teaching experience, access to digital devices, and willingness to participate for one semester. Following baseline TPACK pre-test administration, participants were allocated to experimental (n = 30) and control (n = 30) groups through matched pairing based on pre-test scores, teaching experience, and professional certification status. The

control group continued with regular MGMP (subject teacher working group) activities and was offered delayed treatment after the study.
Participant characteristics were comparable: 68% female, mean age 38.5 years (SD = 7.2), mean teaching experience 12.3 years (SD = 6.8), 75% professionally certified, and 20% postgraduate. Settings included urban (4 schools), suburban (4), and rural (2) locations to enhance external validity. Table 2 presents the demographic characteristics of participants. Statistical analyses confirmed no significant differences between experimental and control groups across all baseline characteristics (all p > .05), supporting the comparability of groups prior to intervention.

Table 2: Demographic characteristics of participants

Characteristic	Experimental Group (n=30)	Control Group (n=30)	Test Statistic	p-value
Gender				
Male	17 (56.7%)	15 (50.0%)	$\chi^2(1) = 0.07$	0.796
Female	13 (43.3%)	15 (50.0%)		
Age (years)	35.02 ± 3.70	36.40 ± 4.05	$t(58) = -1.36$	0.179
Teaching experience (years)	8.98 ± 3.40	9.69 ± 3.43	$t(58) = -0.79$	0.435
Education level				
Bachelor's degree	22 (73.3%)	24 (80.0%)	$\chi^2(1) = 0.09$	0.76
Master's degree	8 (26.7%)	6 (20.0%)		
Professional certification				
Certified	18 (60.0%)	16 (53.3%)	$\chi^2(1) = 0.07$	0.794
Not certified	12 (40.0%)	14 (46.7%)		
School location				
Urban/Suburban/Rural	11/12/2007	10/13/2007	$\chi^2(2) = 0.09$	0.957
Technology access level				
High/Moderate/Low	9/15/2006	8/16/2006	$\chi^2(2) = 0.09$	0.955

Note. M = Mean; SD = Standard Deviation. All baseline comparisons were non-significant (p > .05), indicating successful matching between groups. Chi-square tests were used for categorical variables; independent t-tests for continuous variables.

4.3 Intervention

The experimental group participated in an 18-week PD program (August–December 2023) totalling 54 contact hours: 18 PLC sessions (3 hours each) and three (3) individual coaching sessions (1.5 hours each). Teachers were organized into six PLCs (5 per PLC) by school proximity. The program followed the four IDPC phases: Awakening (Weeks 1–3, 9 hours), Acquiring (Weeks 4–9, 18 hours), Applying (Weeks 10–15, 22.5 hours, including coaching), and Advancing (Weeks 16–18, 9 hours). Details of activities for each phase are presented in Table 3.

Table 3: Professional development program structure based on the IDPC framework

Phase	Sunday	Duration	Main Focus	Key Activities
Awakening	1–3	9 hours (3 PLC sessions)	Building awareness about student diversity, the importance of differentiation, and the role of technology	Student readiness data analysis Exploring Tomlinson's framework Hands-on exploration of adaptive platforms (Khan Academy, Google Forms, Quizizz) SWOT analysis of implementation Setting personal learning goals
Acquiring	4–9	18 hours (6 PLC sessions)	Building knowledge and skills of TK, PK, and CK	Kindergarten (Session 4-5): Mastering Google Classroom, Khan Academy, Google Forms; UX principles PK (Session 6-7): Flexible grouping, scaffolding, tiering CK & PCK (Session 8-9): Learning trajectory, Misconceptions, Multiple representations, Connections between topics
Applying	10–15	22.5 hours (6 PLC sessions + 3 coaching sessions)	Applying knowledge in authentic teaching practice	Design sprint (Week 10-11): Designing differentiated learning units Implementation in class (Week 12-14) Coaching cycles: Pre-observation conference, observation, post-observation conference Peer observation (Week 15)
Advancing	16–18	9 hours (3 PLC sessions)	Reflection, refinement, and sharing expertise	Collaborative analysis of student work using the CASL protocol Showcase presentations between PLCs Holistic reflection and action planning for continuous improvement

4.4 Instruments

Four instruments were used for triangulation. First, the digital pedagogical competence questionnaire, adapted from Baysal (2018) and Archambault and Barnett (2010), comprised 56 items measuring seven TPACK constructs on a five-point Likert scale. Content validity was confirmed by five experts (CVR ≥ 0.80), internal reliability was excellent (α = 0.84–0.91), and CFA confirmed the seven-factor structure (CFI = 0.93, TLI = 0.92, RMSEA = 0.06).

Second, the OPDI, adapted from Stager's (2007) DIOS and Coubergs et al.'s (2017) ADAPT, comprised 24 indicators across four dimensions scored on a four-level rubric (0–3). While construct validity through CFA was not conducted for the

OPDI in this context, a limitation we acknowledge, inter-rater reliability was excellent (κ = 0.78–0.85), and findings were triangulated with other data sources. Third, semi-structured interviews (45–60 minutes) covered five domains with all 30 experimental-group teachers. Fourth, document analysis examined 30-unit plans, 90 reflection journal entries, 90 coaching notes, and 108 PLC meeting minutes.

4.5 Data analysis

Quantitative analyses used SPSS 27.0. Assumptions were tested using Shapiro–Wilk (normality), Levene's test (homogeneity of variance), and group × pretest interaction (homogeneity of regression slopes); all were satisfied ($p > .05$). Paired-samples t-tests assessed within-group changes, while ANCOVA compared adjusted post-test means between groups. Cohen's d was computed for paired comparisons and partial η^2 for ANCOVA, and interpreted using established benchmarks (Cohen, 1988). Missing data (<3%) were handled through listwise deletion after confirming MCAR (missing completely at random); sensitivity analysis confirmed stable results.

Qualitative data were analyzed using Braun and Clarke's (2006) six-phase thematic analysis supported by NVivo 12. Inter-coder agreement exceeded 85% for main themes. Trustworthiness was ensured through data source triangulation, thick description, audit trails, and researcher reflexivity. Integration occurred through joint displays at the interpretation stage.

4.6 Research Ethics

Ethical approval was obtained from the Research Ethics Committee of Universitas Pendidikan Indonesia. All participants provided written informed consent, and confidentiality was maintained through the use of pseudonyms.

5. Result

5.1 Baseline Equivalence

No significant differences existed between groups at baseline in age ($t = 0.45$, $p = .65$), teaching experience ($t = 0.38$, $p = .71$), education level ($\chi^2 = 0.82$, $p = .66$), certification ($\chi^2 = 0.31$, $p = .85$), technology access ($\chi^2 = 1.23$, $p = .54$), or total TPACK pretest scores ($t = 0.73$, $p = .47$). All 30 experimental-group teachers completed the program with 94% PLC session attendance.

5.2 Within-Group Improvement

Table 4 presents paired t-test results for the experimental group. All TPACK dimensions showed significant pre-to-post improvements. The largest effect sizes were found for integrative TPACK ($d = 2.15$), TPK ($d = 2.11$), and TK ($d = 1.98$), confirming H1. Dimensions with higher baselines (CK, PCK) showed smaller but still substantial gains ($d = 1.12$ and 0.95, respectively). The corrected Cohen's d for PK was 1.67, reflecting a large effect consistent with meaningful improvement in pedagogical differentiation strategies.

Table 4: Improving digital pedagogical competence of the experimental group (N=30)

Dimension TPACK	Pre-test M (SD)	Post-test M (SD)	Mean Difference	t	df	p	Cohen's d
TK	2.85 (0.62)	4.12 (0.48)	1.27	12.45	29	<0.001***	1.98
PK	3.43 (0.58)	4.35 (0.52)	0.93	10.87	29	<0.001***	1.67
CK	3.78 (0.55)	4.28 (0.48)	0.50	8.92	29	<0.001***	1.12
TCK	2.72 (0.68)	3.98 (0.56)	1.26	11.34	29	<0.001***	1.86
TPK	2.58 (0.71)	4.05 (0.54)	1.47	13.21	29	<0.001***	2.11
PCK	3.65 (0.61)	4.22 (0.57)	0.57	7.45	29	<0.001***	0.95
TPACK	2.65 (0.73)	4.08 (0.51)	1.43	14.23	29	<0.001***	2.15
Total	3.09 (0.48)	4.15 (0.42)	1.06	16.78	29	<0.001***	2.26

*Notes: M = Mean; SD = Standard Deviation; Cohen's d: 0.2 = small, 0.5 = medium, 0. = large, >1.2 = very large effect; ***p<0.001*

As illustrated in Figure 4, all TPACK dimensions demonstrated large to very large effect sizes (d > 0.8), with integrative competencies (TPK: d = 2.11; TPACK: d = 2.15) showing the strongest intervention effects, thereby supporting H4.

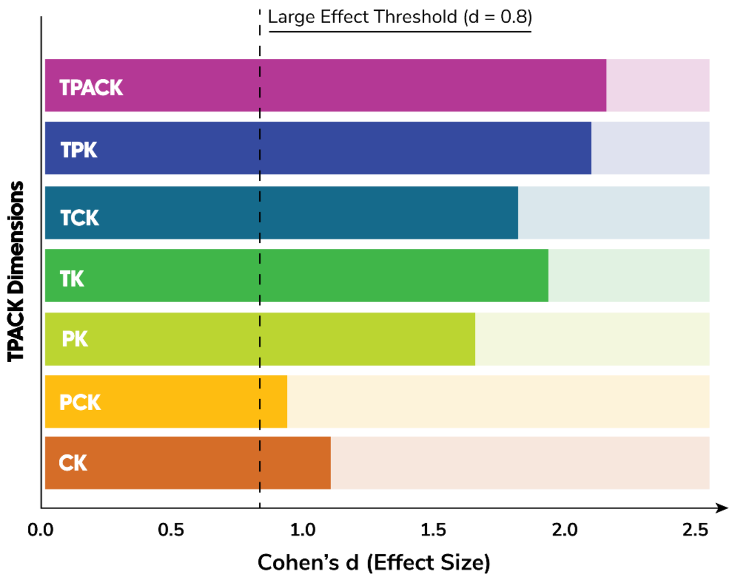

Figure 4: Effect sizes (Cohen's d) across TPACK dimensions

5.3 Between-Group Differences

ANCOVA results (Table 5) confirmed significant between-group differences across all dimensions after controlling for pre-test scores, supporting H2. The largest effects were found for total score (partial $\eta^2 = 0.73$), integrative TPACK ($\eta^2 = 0.66$), and TK ($\eta^2 = 0.63$). The profile plot (Figure 5) illustrates the divergent trajectories, with the experimental group increasing sharply (3.09 to 4.15) while the control group remained relatively stable (3.15 to 3.28).

Table 5: Differences in digital pedagogical competence between experimental and control groups (post-test, controlled for pre-test)

TPACK Dimensions	Post-test Experiment Adjusted M (SE)	Post-test Control Adjusted M (SE)	F	df	p	Partial η²
TK	4.11 (0.08)	3.02 (0.08)	98.42	1, 57	<0.001***	0.63
PK	4.34 (0.09)	3.58 (0.09)	38.27	1, 57	<0.001***	0.40
CK	4.27 (0.08)	3.85 (0.08)	14.32	1, 57	<0.001***	0.20
TCK	3.97 (0.10)	2.88 (0.10)	62.15	1, 57	<0.001***	0.52
TPK	4.04 (0.10)	2.72 (0.10)	89.76	1, 57	<0.001***	0.61
PCK	4.21 (0.09)	3.72 (0.09)	15.88	1, 57	<0.001***	0.22
TPACK	4.07 (0.09)	2.78 (0.09)	111.45	1, 57	<0.001***	0.66
Total	4.14 (0.07)	3.22 (0.07)	156.34	1, 57	<0.001*	0.73

*Note: Adjusted M = Adjusted mean after controlling for pre-test; SE = Standard Error; Partial η²: 0.01 = small, 0.06 = medium, 0.14 = large effect; ***p<0.001*

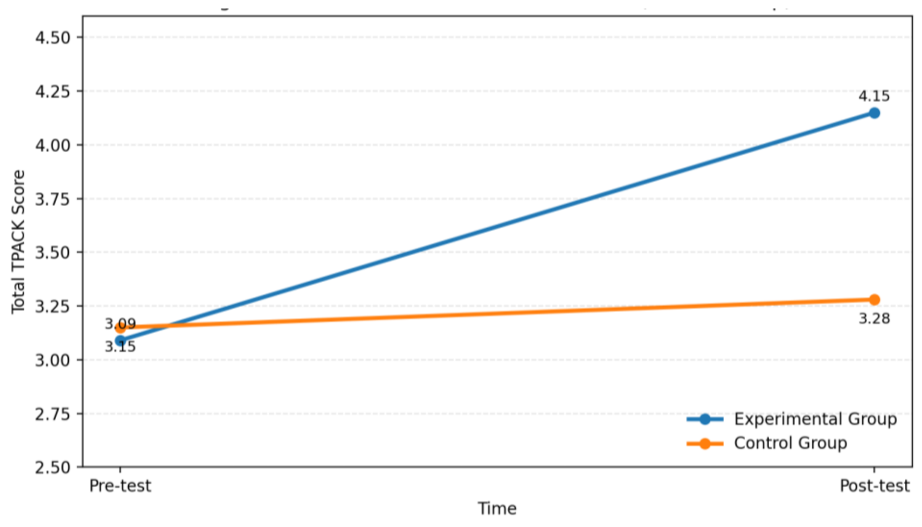

Figure 5: Profile plot Total TPACK: pre-test vs post-test, experiment vs control

5.4 Per-Dimensional Analysis

Comparing effect sizes confirmed H4: integrative TPACK (d = 2.15) and TPK (d = 2.11) showed the greatest gains, followed by TK (d = 1.98), TCK (d = 1.86), PK (d = 1.67), CK (d = 1.12), and PCK (d = 0.95). These dimensions represent areas least addressed in traditional PD, with the lowest baselines providing greater room for growth.

5.5 Changes in Teaching Practices

OPDI results (Table 6) revealed dramatic improvements in differentiated practices. The total score increased from 0.96 to 2.32 (d = 3.38), confirming that competency gains transferred to observable practice. Pre-Instruction showed the largest change (d = 3.15), followed by During Instruction (d = 3.06). At endline, 83% of teachers consistently used pre-assessment and planned differentiation. The experimental group's endline OPDI (M = 2.32) was significantly higher than that of the control group (M = 1.05; t (58) = 11.35, $p < .001$, d = 2.92), confirming H3. Statistical analysis confirmed that the experimental group significantly outperformed the control group in all post-test measures, as summarized in Table 7.

Table 6: Changes in differentiated learning practices (OPDI Score) - Experimental group (N=30)

OPDI Dimensions	Baseline M (SD) [Range: 0-3]	Endline M (SD)	Mean Difference	t	p	Cohen's d
Pre-Instruction (6 indicators)	0.78 (0.45)	2.35 (0.52)	1.57	16.34	<0.001***	3.15
During Instruction (10 indicators)	0.92 (0.38)	2.28 (0.48)	1.36	18.56	<0.001***	3.06
Post-Instruction (4 indicators)	0.65 (0.51)	2.12 (0.58)	1.47	14.87	<0.001***	2.73
Learning Environment (4 indicators)	1.48 (0.62)	2.52 (0.48)	1.04	10.23	<0.001***	1.85
Total OPDI Score	0.96 (0.36)	2.32 (0.45)	1.36	20.45	<0.001*	3.38

*Note: OPDI uses a 4-level rubric (0-3); ***p<0.001*

Table 7: OPDI endline comparison: Experimental vs. control group

Group	N	M	SD	t	p	Cohen's d
Experimental	30	2.32	0.45	11.35	<.001	2.92
Control	30	1.05	0.42			

Figure 6 presents the correlation between TPACK competency gains and observed classroom practice gains. A strong positive correlation was found ($r = 0.799$, $p < .001$), with TPACK gains explaining 63.8% of the variance in OPDI implementation gains. This demonstrates significant transfer from knowledge acquisition to authentic behavioral change in classroom practice, supporting the ecological validity of the IDPC framework intervention.

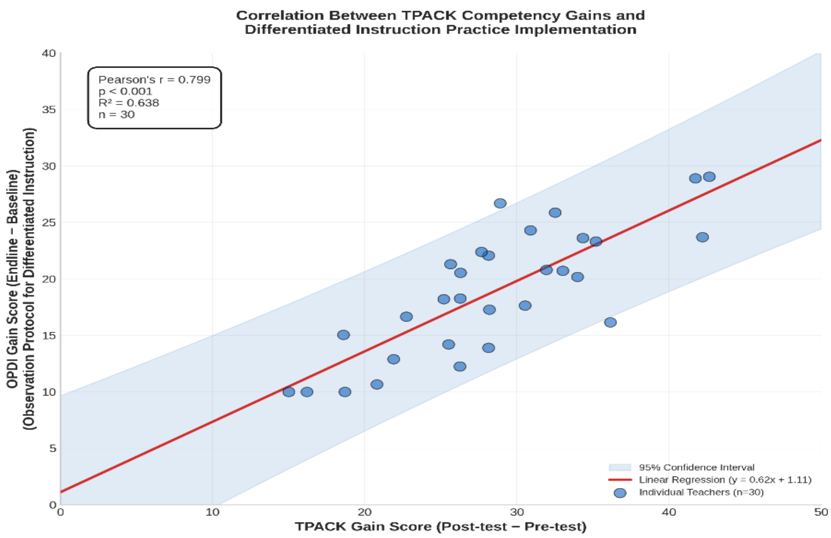

Figure 6: Knowledge-to-practice transfer: TPACK gains predict classroom implementation

5.6 Qualitative Findings

5.6.1 Theme 1: Transformative mindset shifts

Teachers described "seeing students with new eyes" after analyzing pre-assessment data. Teacher ES07 reflected: "When I actually analyzed their pre-assessment data in detail, I was shocked. Their variation was much greater than I had imagined." This shift moved teachers from blaming student abilities to questioning appropriate support structures.

5.6.2 Theme 2: Enhanced technological confidence

Senior teachers who initially experienced technological anxiety progressed through a "fear to knowledge to skill" journey. Teacher ES04 noted: "Now, I can create my own Google Classroom, assign differentiated activities, and understand what dashboards mean." Individual coaching was identified as a critical turning point.

5.6.3 Theme 3: Improved differentiation practices

Teachers moved from shallow understanding of differentiation to systematic implementation: formative assessments, flexible grouping, tiered activities, choice boards, and gradual scaffolding. The design–implementation–reflection cycle with coaching support facilitated this transition.

5.6.4 Theme 4: PLCs as sustained support systems

PLCs were identified as the most valuable program component, providing cognitive, affective, and practical support. Several groups committed to continuing beyond the program. Teacher ES15 stated: "This PLC has become my professional lifeline."

5.6.5 Theme 5: Persistent implementation challenges

Time constraints, large class sizes (averaging 35 students), and unstable infrastructure remained barriers. Teachers adopted pragmatic adaptations: collaborative planning, group-based (rather than individual) differentiation, and "start small" strategies.

Figure 7 presents the thematic network map synthesizing qualitative findings from interviews and document analysis. Five main themes emerged, revealing a systematic progression from initial mindset transformation (Theme 1) through technological confidence building (Theme 2), pedagogical innovation (Theme 3), and enhanced student engagement (Theme 4), culminating in sustained practice change (Theme 5). Notably, the feedback loop from sustained practice to technological confidence suggests a self-reinforcing competency development cycle, supporting the long-term viability of IDPC framework implementation.

Figure 7: Thematic network map: Qualitative analysis of IDPC framework implementation

5.7 Document Analysis Findings

Analysis of 30 differentiated unit plans revealed progressive sophistication in technology integration across program phases. Early designs (Weeks 10–11) primarily used technology for content delivery, while later designs incorporated diagnostic assessment, tiered tasks, and formative feedback loops. Reflection journals (90 entries) documented shifts from surface-level technical descriptions to deeper pedagogical reasoning about tool selection. Coaching notes confirmed that teachers who received targeted feedback on pedagogical intent, rather than technical operation, showed faster growth in TPK. PLC meeting minutes documented increasing collaborative depth, with later sessions featuring data-driven discussions and artifact-based inquiry rather than procedural matters.

5.8 Integration: Joint Display

Table 8 integrates quantitative and qualitative findings. Convergence was observed across all major dimensions: the largest quantitative gains (TPACK, d = 2.15) were explained qualitatively by teachers' reports of learning to purposefully connect technology to differentiation. The dramatic OPDI improvement (d = 3.38) was supported by observed shifts from uniform to differentiated instruction. Mindset change, though not measured quantitatively, emerged as a foundational mechanism enabling competency and practice transformation.

Table 8: Joint display: Integration of quantitative and qualitative findings

Aspect	Quantitative Findings	Qualitative Findings	Integrated Interpretation
Technological Knowledge (TK)	Very large improvement (d=1.98); post-test average reached 4.12	Teachers describe a journey "from fear to skill"; hands-on learning and peer support are crucial	The program successfully built a TK through supportive active learning, while also addressing the technological anxiety experienced by teachers at the beginning
Pedagogical Knowledge (PK)	Large improvement (d=1.73); post-test average reached 4.35	Teachers previously understood the concept of differentiation in theory, but did not know how to implement it until joining this program	The design-implementation-reflection cycle supported by coaching successfully transfers pedagogical knowledge into real practice in the classroom
TPACK (Integrative)	The greatest increase (d=2.15); The most significant between-group difference ($\eta2=0.66$)	Teachers learn how technology facilitates differentiated pedagogy through hands-on experiences and authentic applications	Integration is the highest level of competency; this success is achieved through situated learning in a real teaching context
Teaching Practice	Observation score (OPDI) increased very sharply (d=3.38); Change from one-size-fits-all to differentiation	Teachers implemented concrete changes: initial assessments, tiered activities, flexible grouping, and the use of technology for differentiation	Real practice changes confirm that competency improvements are not only theoretical, but are realized in classroom implementation
Mindset	Not measured quantitatively	A theme of a transformative mindset shift emerged; teachers saw students "with new eyes" (a shift from a fixed to a growth mindset)	A change in mindset is the main foundation that allows for changes in competencies and other instructional practices
PLC as a PD Model	100% retention rate and 94% attendance (very high engagement indicators)	Teachers describe PLCs as a "support system" and community; considered the most valuable aspect of the program	PLCs are effective because they create a social learning environment that is supportive, collaborative, and has positive accountability

Aspect	Quantitative Findings	Qualitative Findings	Integrated Interpretation
Challenge	Identified through teacher reflection journals	Time constraints, large class sizes, limited infrastructure, and initial resistance from student	The challenges on the ground are real and need to be addressed through systemic support and adequate infrastructure for program sustainability

6. Discussion

The findings consistently support the hypothesis that a systematically designed PD program based on the IDPC framework can effectively build teachers' digital pedagogical competencies. The large effect sizes across all TPACK dimensions (d = 0.95–2.15) are consistent with, and exceed, the meta-analytic findings of Yeh et al. (2021), who reported d = 0.76 for TPACK-based PD. This difference is attributable to the program's greater intensity (54 hours vs. 24 hours median), integration of multiple PD modalities, and context-specific focus on mathematics differentiation. The finding that TPK and integrative TPACK showed the greatest gains confirms that these dimensions are "missing links" in traditional PD (Angeli & Valanides, 2020). The iterative cycle of technology exploration, pedagogical application, classroom implementation, and reflection facilitated the development of TPACK as "knowledge-in-action" (Koehler et al., 2013).

The dramatic improvement in OPDI scores (d = 3.38) provides strong evidence that the program transformed practice, not merely knowledge. This is consistent with Kraft et al.'s (2018) finding that coaching with observation-feedback cycles produces greater practice transfer. Qualitative data revealed four transfer mechanisms: relevance, scaffolded implementation, peer modelling, and supportive accountability, aligning with Bandura's (1986) social cognitive theory. PLCs emerged as the most valued component, providing cognitive, affective, and practical support. This extends the PLC literature (Stoll et al., 2006; Vescio et al., 2008) by demonstrating that in contexts with limited infrastructure, collaborative communities serve as essential buffers against implementation challenges. Several PLCs developed characteristics of "mature communities of practice" (Lave & Wenger, 1991), an important sustainability indicator.

The challenges identified, including time constraints, large class sizes, and infrastructure limitations, align with global differentiation barriers (Smale-Jacobse et al., 2019). The success of digital pedagogies depends not only on teacher competence but also on structural readiness and equitable access, as similarly demonstrated in the Lebanese context by Badawi and Adiyono (2026). Teachers' pragmatic adaptations suggest that with adequate support, challenges can be navigated through collaborative planning and group-based differentiation.

This study has limitations. The quasi-experimental design without random assignment limits causal claims. TPACK data relied primarily on self-reports, although triangulation with OPDI observations and document analysis mitigated this concern. The sample was limited to Jambi City, and the study measured only immediate post-program effects. Future research should employ randomized controlled trials, longitudinal follow-ups, and student outcome measures to strengthen the evidence base.

7. Implications

Theoretically, this study advances TPACK by specifying how integrative knowledge develops through situated, iterative PD in the context of adaptive differentiation. Practically, the IDPC framework provides a replicable model for PD programs that can be adapted to diverse educational contexts. For policy, scaling adaptive differentiation requires investment in both digital infrastructure and organizational supports, including protected collaborative time, coaching capacity, and leadership that encourages pedagogical experimentation.

8. Conclusion

This study developed, implemented, and evaluated the IDPC framework, demonstrating its efficacy as a PD model for enhancing mathematics teachers' digital pedagogical competencies. The program produced large-to-very-large effects across all TPACK dimensions ($d = 0.95$–2.15) and transformed classroom practices from uniform instruction to systematic differentiation (OPDI $d = 3.38$). PLCs served as vital support systems, and the iterative design–implementation–reflection cycle facilitated genuine transfer from knowledge to practice. While challenges of time, infrastructure, and class size persist, the IDPC model equips teachers with the integrative knowledge and pedagogical agency to navigate these obstacles. Future research should examine long-term sustainability, student learning outcomes, and cross-cultural transferability of the framework.

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10. Use of AI Statement

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) as an AI-assisted language tool for improving grammar, language clarity, readability, and academic writing style. All AI-generated suggestions were carefully reviewed, edited, and validated by the authors. The authors take full responsibility for the content of the manuscript. No AI tools were used for data collection, data analysis, interpretation of findings, or the generation of research results and conclusions.

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