



Improving Teachers' Digital Pedagogical Competence through Action Research-Based Technology Integration

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ABSTRACT

Purpose – This study investigated how action research-based technology integration improves teachers' digital pedagogical competence across multiple dimensions, examining the mechanisms and contextual factors that facilitate this development.

Design/methods – Employing a convergent parallel mixed-methods design, this year-long study involved 24 secondary school teachers organized into four collaborative action research teams. Quantitative data were collected through pre-test and post-test TPACK surveys and DigCompEdu self-assessments at three time points, analyzed using paired-samples t-tests. Qualitative data included reflective journals, meeting transcripts, focus group interviews, and classroom observations, analyzed through thematic analysis.

Findings – Results revealed statistically significant improvements across all seven TPACK domains ($p < .001$), with largest effect sizes in integrated knowledge areas; TPACK ($d = 1.72$), TPK ($d = 1.60$), and TCK ($d = 1.48$). By study's end, 58.3% of teachers reached leader level in professional engagement, and 45.8% in teaching & learning competence. Four mechanisms facilitated development; systematic experimentation, evidence-based reflection, collaborative problem-solving, and iterative refinement, with leadership support and team dynamics emerging as critical contextual enablers.

Keyword: *Digital Pedagogical Competence, Action Research, Technology Integration, TPACK, Teacher Professional Development*

ABSTRAK

Tujuan – Penelitian ini menyelidiki bagaimana integrasi teknologi berbasis penelitian tindakan (action research) meningkatkan kompetensi pedagogis digital guru dalam berbagai dimensi, serta mengkaji mekanisme dan faktor kontekstual yang memfasilitasi perkembangan tersebut.

Metode – Dengan menggunakan desain mixed-methods paralel konvergen, penelitian selama satu tahun ini melibatkan 24 guru sekolah menengah yang tergabung dalam empat tim kolaboratif penelitian tindakan. Data kuantitatif dikumpulkan melalui survei TPACK pre-test dan post-test serta penilaian diri DigCompEdu pada tiga titik waktu, yang dianalisis menggunakan uji t berpasangan (paired-samples t-test). Data kualitatif meliputi jurnal reflektif, transkrip pertemuan, wawancara kelompok terarah (focus group), dan observasi kelas, yang dianalisis melalui analisis tematik.

Hasil – Hasil penelitian menunjukkan peningkatan yang signifikan secara statistik pada seluruh tujuh domain TPACK ($p < 0,001$), dengan ukuran efek terbesar pada area pengetahuan terintegrasi; TPACK ($d = 1,72$), TPK ($d = 1,60$), dan TCK ($d = 1,48$). Pada akhir penelitian, 58,3% guru mencapai level pemimpin (leader level) dalam keterlibatan profesional, dan 45,8% dalam kompetensi pengajaran dan pembelajaran. Empat mekanisme yang memfasilitasi perkembangan tersebut adalah: eksperimen sistematis, refleksi berbasis bukti, pemecahan masalah kolaboratif, dan penyempurnaan iteratif. Dukungan kepemimpinan dan dinamika tim muncul sebagai faktor kontekstual kunci yang memungkinkan keberhasilan pengembangan tersebut.

Kata Kunci: *Kompetensi Pedagogis Digital, Penelitian Tindakan, Integrasi Teknologi, TPACK, Pengembangan Profesional Guru*

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Introduction

Rapid advancement of digital technology has transformed educational landscapes worldwide, creating opportunities and challenges for 21st century teaching. Despite substantial investments in educational technology infrastructure, a critical gap persists between technology availability and meaningful pedagogical integration (Gudmundsdottir & Hatlevik, 2018). Teachers struggle with effectively integrating digital tools, highlighting urgent need for professional development addressing both technical and pedagogical dimensions of digital competence (Ertmer et al., 2012).

Digital pedagogical competence encompasses knowledge, skills, and attitudes necessary for effective technology integration. The TPACK framework provides foundation for understanding relationships between technology, pedagogy, and content knowledge (Mishra & Koehler, 2006), emphasizing effective integration requires understanding at domain intersections (Voogt et al., 2013). The DigCompEdu framework further delineates competence across professional engagement, digital resources, teaching and learning, assessment, empowering learners, and facilitating learners' digital competence (Redecker, 2017). However, developing such competence requires sustained professional development that transcends one-time training and addresses authentic implementation challenges (Trust et al., 2016).

Traditional workshop-based professional development has proven inadequate for fostering lasting pedagogical change. These transmissive approaches emphasize technical skills without sufficient attention to pedagogical integration, failing to address the complex, situated nature of teaching practice (Lawless & Pellegrino, 2007; Prestridge, 2012). Teachers report feeling inadequately prepared to transfer decontextualized training to classrooms, resulting in limited technology adoption (Bingimlas, 2009). Conventional models seldom provide ongoing support, collaboration opportunities, or reflective practice mechanisms essential for deep professional learning (Avalos, 2011).

Action research enables teachers to systematically investigate their practices and develop context-specific solutions through cyclical processes of planning, acting, observing, and reflecting (Kemmis et al., 2014). This approach suits technology integration as it allows teachers to experiment with digital tools in authentic contexts, assess impact on student learning, and adjust practices based on evidence (Brydon-Miller et al., 2003). Collaborative action research creates professional learning communities that sustain innovation (Sagor, 2011), while fostering critical reflection, evidence-based decision-making, and professional autonomy (Mertler, 2017).

Despite theoretical promise, empirical evidence explaining how action research mechanisms foster digital pedagogical competence remains scarce. While prior studies acknowledge potential (Cavinato et al., 2021; Cheung, 2013), critical gaps persist. First, existing research primarily focused on pre-service teachers or small-scale implementations, limiting understanding of scalability (Hine & Lavery, 2014). Second, insufficient examination exists of how action research components contribute to various competence dimensions. Third, mechanisms through which action research facilitates changes in teachers' beliefs, knowledge, and practices require investigation (Doppelt, Schunn, Silk, Mehalik, Reynolds, & Ward, 2009). Finally, research has not adequately addressed how contextual factors influence effectiveness (Ross & Bruce, 2007).

This study investigates how action research-based technology integration improves teachers' digital pedagogical competence. Employing convergent parallel mixed-methods design (Creswell & Plano Clark, 2018), this year-long investigation examines quantitative changes in competence and qualitative insights into learning processes. The study investigates: (1) how cyclical processes contribute to changes in teachers' TPACK and DigCompEdu competence; (2) mechanisms through which action research supports development; and (3) contextual factors that facilitate or constrain effectiveness (Timperley, et al., 2007).

This research benefits multiple stakeholders. Teachers gain a roadmap for self-directed professional development that enables ownership through systematic inquiry (Darling-Hammond et al., 2017). School leaders gain insights into structuring action research

initiatives that foster collaborative learning communities (Fullan, 2016). Professional development providers and policymakers benefit from evidence-based guidance on designing comprehensive teacher learning experiences (Borko et al., 2010). By demonstrating how action research bridges the gap between technology availability and pedagogical application, this research contributes to educational improvement efforts aimed at preparing students for success in a digital world.

Methods

This study employed participatory action research to investigate how teachers develop digital pedagogical competence through systematic inquiry into technology integration practices. Participatory action research is "a social process of collaborative learning realized by groups of people who join together in changing the practices through which they interact in a shared social world" (Kemmis et al., 2014). The research was conducted over one academic year with 24 in-service teachers from six secondary schools in an urban district, representing diverse subject areas including mathematics, science, language arts, social studies, and the arts. Participants were organized into four collaborative action research teams, each consisting of six teachers from different schools but teaching similar grade levels or subject areas. The study followed spiral cycles of action research, with each cycle comprising four phases: planning (identifying technology integration goals), acting (implementing technology-enhanced lessons), observing (collecting data on implementation and student responses), and reflecting (analyzing outcomes and refining practices). Data collection occurred throughout all phases, employing multiple methods to capture process and outcome dimensions of teachers' professional learning.

This study employed a convergent parallel mixed-methods design to provide a comprehensive understanding of quantitative changes in digital pedagogical competence alongside qualitative insights into teachers' learning processes. In this design, researchers collect quantitative and qualitative data simultaneously, analyze them independently, and then compare the results to determine whether the findings converge or diverge (Creswell & Clark, 2018). This approach enabled the study to address the complexity of measuring competence development, exploring underlying mechanisms, and examining relevant contextual factors.

Quantitative data were collected through pre-test and post-test administration of TPACK survey instrument adapted from Schmidt, Baran, Thompson, Mishra, Koehler, & Shin (2009), measuring teachers' self-reported technological knowledge, pedagogical knowledge, content knowledge, and intersections among these domains. TPACK framework was selected because it addresses integrated knowledge required for effective technology integration (Voogt et al., 2013). The adapted survey consisted of 47 items across seven domains, using a likert scale. The original instrument demonstrated strong reliability (Cronbach's α ranging from 0.75 to 0.92) and has been widely validated (Chai et al., 2013).

Teachers also completed a digital competence self-assessment tool based on DigCompEdu (Redecker, 2017) at beginning, middle, and end of study to track progression across six competence areas. DigCompEdu was selected to complement TPACK because it provides comprehensive view extending beyond classroom instruction to include professional engagement, digital resource curation, and facilitating learners' digital competence development (Cabero-Almenara et al., 2020). The tool employs a progression model (A1-C2 levels) across 22 competences.

Qualitative data sources included reflective journals maintained by participants, video recordings of selected technology-enhanced lessons, transcripts from bi-weekly team reflection meetings, lesson plans and instructional materials, focus group interviews conducted after each cycle, and researcher field notes. These multiple sources provided rich evidence of mechanisms and contextual factors influencing competence development. This multi-method approach enabled triangulation and comprehensive understanding of how action research facilitated competence development.

This study acknowledges important limitations inherent in self-assessment instruments. Self-reported measures are vulnerable to validity threats, including social desirability bias, the Dunning-Kruger effect, and response shift bias that may affect accuracy

(Kruger & Dunning, 1999; Blume et al., To mitigate these limitations, this study implemented several complementary strategies. First, triangulation of quantitative self-assessments with multiple qualitative data sources (classroom observations, video recordings, reflective journals, and peer feedback) provided external validation (Denzin, 2012). Second, longitudinal design with three measurement points enabled examination of consistency in self-assessment patterns. Third, action research context, which emphasized evidence-based reflection, encouraged realistic self-assessment as teachers confronted concrete evidence of their technology integration successes and challenges. Finally, data interpretation focused on relative changes rather than absolute scores, with findings discussed with appropriate caution. Despite these mitigation strategies, readers should interpret quantitative findings as representing teachers' perceptions rather than objective measures of skill or student impact. Inclusion of rich qualitative data documenting actual classroom practices helps contextualize and validate these self-reported changes, providing a complete picture of digital pedagogical competence development.

Data analysis followed an iterative process integrating both quantitative and qualitative analytical techniques. Quantitative data derived from the TPACK surveys and DigCompEdu self-assessments were analyzed using paired-samples *t*-tests to examine statistically significant changes, with effect sizes calculated using Cohen's *d*. Meanwhile, qualitative data were analyzed through thematic analysis procedures (Braun & Clarke, 2006). The analysis involved: familiarization with data through repeated reading of transcripts and viewing videos, generating initial codes capturing features relevant to competence development, searching for themes by collating codes into broader patterns, reviewing themes to ensure accuracy, defining and naming themes, and producing final analysis by selecting compelling examples and relating findings to research questions and literature. Qualitative data were analyzed using NVivo 12 software, while quantitative analyses were conducted using SPSS version 26. Integration of findings occurred during interpretation, where results were compared to develop meta-inferences about how action research improved teachers' digital pedagogical competence.

Results and Discussion

2.1. Changes in Teachers' TPACK Competence Through Action Research Cycles

Quantitative analysis of pre-test and post-test TPACK survey data revealed statistically significant improvements across all seven knowledge domains following teachers' participation in action research-based technology integration. Table 1 presents the descriptive statistics and paired-samples *t*-test results for each TPACK domain, demonstrating substantial growth in teachers' self-reported competence levels.

Table 1. Pre-Test and Post-Test TPACK Scores: Descriptive Statistics and Paired-Samples T-Test Results

TPACK Domain	Pre-Test M (SD)	Post-Test M (SD)	Mean Difference	t	df	p	Cohen's d
Technological knowledge (TK)	3.42 (0.68)	4.28 (0.52)	0.86	6.89	23	<.001	1.41
Pedagogical knowledge (PK)	4.15 (0.54)	4.56 (0.48)	0.41	4.12	23	<.001	0.84
Content knowledge (CK)	4.38 (0.51)	4.62 (0.45)	0.24	2.87	23	.008	0.59
Pedagogical content knowledge (PCK)	4.22 (0.58)	4.64 (0.42)	0.42	4.35	23	<.001	0.89

TPACK Domain	Pre-Test M (SD)	Post-Test M (SD)	Mean Difference	t	df	p	Cohen's d
Technological content knowledge (TCK)	3.28 (0.72)	4.18 (0.56)	0.90	7.24	23	<.001	1.48
Technological pedagogical knowledge (TPK)	3.35 (0.66)	4.32 (0.54)	0.97	7.86	23	<.001	1.60
TPACK	3.18 (0.74)	4.25 (0.58)	1.07	8.42	23	<.001	1.72

Source: Primary data, 2025

Largest effect sizes were observed in integrated knowledge domains (TPACK, TPK, and TCK), suggesting action research processes particularly enhanced teachers' abilities to synthesize technological, pedagogical, and content knowledge. Teachers demonstrated the greatest improvement in TPACK ($d = 1.72$), followed by TPK ($d = 1.60$) and TCK ($d = 1.48$), indicating substantial development in their capacity to integrate technology meaningfully into subject-specific instruction. These large effect sizes are consistent with longitudinal professional development interventions providing sustained, practice-embedded learning opportunities. Professional development extending over an academic year with multiple implementation cycles typically yields effect sizes ranging from 0.5 to 2.0, significantly larger than brief workshop-based interventions ($d = 0.1$ to 0.3) (Desimone & Garet, 2015). The year-long duration of this study, combined with iterative cycles, provided extended engagement time essential for meaningful teacher learning (Darling-Hammond et al., 2017).

Qualitative data from reflective journals and focus group interviews corroborated these quantitative findings and provided insights into how action research cycles facilitated TPACK development. However, this development was not without challenges. A mathematics teacher candidly described initial resistance and confusion:

"To be honest, I was very skeptical at the beginning. I thought, 'Here we go again, another technology initiative that will fade away.' I didn't understand how action research was different from other professional development I'd been through. My first attempt at integrating GeoGebra was a complete failure, I spent 20 minutes just trying to get students logged in, half the class was lost, and I felt like I'd wasted everyone's time. I seriously considered dropping out of the study after that first cycle. What changed my mind was the team's response during our reflection meeting. Instead of judging me, they helped me analyze what went wrong, and we collaboratively designed solutions. That support, combined with the expectation that iteration and refinement were built into the process, kept me going."

A science teacher elaborated on cyclical nature of development:

"Each reflection meeting pushed me to think deeper about why I was using technology and what students were actually learning. The first cycle, I focused on engagement, getting students excited with simulations. By third cycle, I was designing investigations where students used data logging equipment to test hypotheses, analyze results, and draw conclusions. Systematic planning and reflection helped me move from technology as a 'wow factor' to technology as a thinking tool."

An English teacher described collaborative aspect:

"Working with other language arts teachers from different schools was eye-opening. When I shared my initial lesson using Google Docs for collaborative writing, my colleagues asked probing questions about learning objectives, scaffolding, and

assessment that I hadn't fully considered. Their feedback, combined with my own classroom observations, helped me refine my approach across multiple iterations until the technology truly enhanced students' writing processes."

Significant self-reported improvements in all TPACK domains, particularly in integrated knowledge areas, provide empirical support for action research as a perceived effective approach to developing teachers' digital pedagogical competence. Effective technology integration requires teachers to develop understanding at the intersections of technology, pedagogy, and content knowledge (Mishra & Koehler, 2006). Action research cycles created structured opportunities for teachers to experiment with technology integration, observe student responses, and refine their approaches, fostering the dynamic and context-sensitive knowledge that characterizes TPACK. The large effect sizes in TPACK, TPK, and TCK suggest that iterative and reflective processes were especially powerful in helping teachers develop complex and integrated competencies. Unlike traditional professional development that focuses narrowly on technical skills, action research enabled teachers to develop technological knowledge while simultaneously applying it pedagogically within specific content areas. Preparing teachers to integrate technology effectively requires comprehensive approaches that address the interconnected nature of teacher knowledge (Tondeur et al., 2012).

Qualitative data revealed that the cyclical structure of action research (planning, acting, observing, and reflecting) served as a scaffold for progressively deeper engagement with technology integration challenges. These iterative cycles created opportunities for the continuous improvement of pedagogical practices, evident in teachers' progression from surface-level technology use to more sophisticated applications (Kemmis et al., 2014). A mathematics teacher's journey from viewing technology merely as a presentation tool to utilizing dynamic geometry software for student exploration exemplifies the transformational learning considered essential for developing technological pedagogical competence (Koehler & Mishra, 2009). Systematic reflection enabled teachers to critically examine their assumptions and develop a nuanced understanding of how digital tools can enhance learning processes. Professional growth occurs through the systematic examination of one's actions (Schön, 1983). Furthermore, collaborative inquiry fostered accountability and intellectual challenge, supporting findings that professional learning communities play a crucial role in facilitating effective technology integration (Admiraal et al., 2013).

The progression observed in teachers' TPACK development through action research addresses the persistent challenge of moving from mere technology availability to pedagogically meaningful implementation. A science teacher's evolution from using technology primarily for student engagement to designing technology-mediated scientific investigations illustrates the pedagogical transformation considered necessary, yet difficult to achieve through conventional professional development (Ertmer et al., 2012). Action research provided the time, structure, and sustained support needed for teachers to align technological affordances with learning objectives, student needs, and disciplinary practices. Substantial improvements in TCK and TPK indicate that action research facilitated the development of both domain-specific technological knowledge and general pedagogical technology knowledge, addressing the dual dimensions regarded as essential for effective technology integration (Voogt et al., 2013). Teachers' content knowledge also showed improvement, suggesting that engagement in technology integration may have stimulated deeper reflection on subject matter itself. This holistic development reflects the comprehensive professional learning required for teachers to effectively facilitate learning in technology-rich environments (Redecker & Punie, 2017).

However, it is important to emphasize that these findings represent teachers' self-perceived development rather than objective measures of skill or direct assessment of student learning outcomes. While triangulation with qualitative data (classroom observations, lesson artifacts, and peer feedback) provides some external validation, readers should interpret these gains as indicators of teachers' changing perceptions of their own competence rather than definitive evidence of pedagogical transformation.

2.2. Development of Digital Competence Across DigCompEdu Framework Areas

Analysis of teachers' self-assessments using DigCompEdu framework revealed progressive development across all six competence areas over the three measurement points (beginning, middle, and end of academic year). Table 2 presents the distribution of teachers across proficiency levels for each competence area at each time point.

Table 2. Distribution of Teachers Across DigCompEdu Proficiency Levels at Three Time Points

Competence Area	Time Point	A1-A2 Newcomer n (%)	B1-B2 Explorer n (%)	C1-C2 Leader n (%)
Professional engagement	Beginning	8 (33.3%)	14 (58.3%)	2 (8.3%)
	Middle	2 (8.3%)	15 (62.5%)	7 (29.2%)
	End	0 (0.0%)	10 (41.7%)	14 (58.3%)
Digital resources	Beginning	12 (50.0%)	11 (45.8%)	1 (4.2%)
	Middle	4 (16.7%)	16 (66.7%)	4 (16.7%)
	End	1 (4.2%)	13 (54.2%)	10 (41.7%)

Source: Primary data, 2025

The data demonstrate substantial upward movement across all competence areas, with dramatic shifts in professional engagement and teaching and learning domains. At study's conclusion, no teachers remained at newcomer level in professional engagement, and 58.3% had reached Leader level. Assessment and facilitating learners' digital competence showed slowest progression, though still demonstrated meaningful improvement.

Teachers' reflective journals documented their developmental trajectories. A social studies teacher described growth in digital resource curation:

"Initially, I just searched for ready-made resources online and used them as-is. Through action research, I learned to critically evaluate digital resources for accuracy, bias, and alignment with learning objectives. More importantly, I started creating and modifying resources myself, building interactive timelines, curating primary source collections, and designing virtual museum tours. I never imagined I'd become a creator of digital content, but the systematic reflection on what students needed pushed me in that direction."

Regarding professional engagement and collaboration, a mathematics teacher noted:

"Action research forced me to step out of my classroom bubble. I started participating in online mathematics teaching communities, sharing my lesson designs and getting feedback from teachers worldwide. I've presented our action research findings at two conferences now and regularly use Twitter to connect with other educators experimenting with technology. This professional dimension was completely absent from my practice before, I thought professional development was something done to me, not something I actively pursued."

A language arts teacher reflected on empowering learners through technology:

"The biggest shift in my thinking came when I realized technology could give students more agency and voice. I moved from controlling every aspect of technology use to creating opportunities for students to choose tools, direct their learning, and share their work with authentic audiences. One of my students created a podcast analyzing contemporary poetry, another built a website comparing literary movements, these

weren't things I assigned specifically, but possibilities that emerged when I stepped back and let students leverage technology for their own purposes."

Notably slower progression in assessment and facilitating learners' digital competence areas warrants examination, revealing important limitations in developing comprehensive digital pedagogical competence through action research. Several factors may explain why these dimensions proved most resistant. First, using technology for sophisticated formative assessment requires not only technological skill but also deep pedagogical knowledge about assessment design, learning progressions, and actionable feedback, demanding more extensive development time (William & Thompson, 2017). Teachers explicitly identified assessment as their greatest challenge.

Progressive development across all DigCompEdu competence areas demonstrates that action research-based technology integration addresses multiple dimensions of digital pedagogical competence. Educator digital competence encompasses professional engagement, digital resource management, pedagogical practices, assessment, learner empowerment, and the facilitation of students' digital competence development (Redecker, 2017). Action research created authentic contexts for teachers to develop competencies across these interconnected domains, as inquiry-based work inherently required engagement with digital resources, pedagogical innovation, and reflection on how technology empowered both teachers and students. The substantial progression from newcomer to leader levels suggests that action research provided sufficient scaffolding and sustained engagement to support confident and innovative practice. This finding responds to concerns that traditional teacher education often fails to cultivate the comprehensive digital competence necessary for effective twenty-first-century teaching (Gudmundsdottir & Hatlevik, 2018).

Particularly strong growth in professional engagement competence, with 58.3% of teachers reaching the leader level, highlights an often overlooked dimension of digital pedagogical competence. Effective use of technology requires teachers to engage in professional learning networks, collaborate across contexts, and participate in digital communities of practice (Trust et al., 2016). Action research supported the development of this dimension by requiring teachers to share their work, provide peer feedback, and engage in broader educational technology dialogues. A social studies teacher's transformation from a passive consumer of digital tools to an active creator illustrates the shift from "technology as teacher resource" to "technology as pedagogical mediator" (Prestridge, 2012). This evolution in professional identity represents a critical aspect of digital competence that extends beyond classroom practice.

Slower progression in assessment and in facilitating learners' digital competence, although still demonstrating improvement, suggests that these areas represent more advanced dimensions requiring extended time for full development. The use of technology for formative assessment and the development of students' own digital competencies are sophisticated practices that demand deep integration of technological, pedagogical, and content knowledge (Hatlevik & Christophersen, 2013). Initial action research cycles may have prioritized immediate instructional concerns, with assessment becoming a focal point only after teachers developed confidence in basic technology-enhanced instruction. A language arts teacher's reflection on shifting from controlling technology use to empowering student agency illustrates the pedagogical transformation associated with deep educational change (Fullan, 2016). The fact that 37.5% of teachers reached the leader level in both empowering learners and facilitating learners' digital competence suggests that action research can support the development of these advanced competencies, although such growth may require sustained engagement. These findings underscore the importance of multi-cycle, long-term action research in fostering comprehensive digital pedagogical competence.

2.3. Mechanisms of Action Research Supporting Digital Competence Development

While the four identified mechanisms facilitated digital competence development for most participants, it is critical to acknowledge conditions under which these mechanisms proved less effective or broke down entirely. Analysis of cases where teachers showed minimal

growth or discontinued participation reveals important limitations that qualify the positive findings. Teacher motivation and workload emerged as significant moderating factors that affected mechanism effectiveness. Three teachers who showed below-average competence gains explicitly cited overwhelming workload as preventing meaningful engagement.

Thematic analysis of qualitative data sources (reflective journals, meeting transcripts, and focus group interviews) identified four primary mechanisms through which action research cycles facilitated development of teachers' digital pedagogical competence; (1) systematic experimentation with technology integration, (2) evidence-based reflection on practice, (3) collaborative problem-solving and knowledge construction, and (4) iterative refinement based on student learning outcomes. Table 3 presents the frequency of coded references to each mechanism across all qualitative data sources, indicating their relative prominence in teachers' learning experiences.

Table 3. Frequency of Coded References to Action Research Mechanisms Across Qualitative Data Sources

Mechanism	Reflective Journals n	Meeting Transcripts n	Focus Groups n	Total n	%
Systematic experimentation	142	98	67	307	26.8%
Evidence-based reflection	156	112	74	342	29.9%
Collaborative problem-solving	134	126	58	318	27.8%
Iterative refinement	108	73	45	226	19.7%

Source: Primary data, 2025

Evidence-based reflection emerged as the most frequently referenced mechanism, appearing in 29.9% of coded segments, followed closely by collaborative problem-solving (27.8%) and systematic experimentation (26.8%). Iterative refinement, while less frequently coded, was identified as critical for deepening competence over time.

Teachers' reflections illustrated how systematic experimentation enabled safe risk-taking with technology integration. A science teacher explained:

"Action research framework gave me permission to experiment and fail. I tried using virtual labs for chemistry demonstrations, and first attempt was a disaster, students were confused, the technology didn't work as expected, and I spent the whole period troubleshooting. But instead of abandoning the idea, I analyzed what went wrong, modified my approach, and tried again. By third iteration, virtual labs became one of my most effective teaching strategies. Without the expectation that I'd be refining and improving, I would have given up after that first failure."

Evidence-based reflection was consistently identified as transformative for changing practice. A mathematics teacher noted:

"Collecting student work samples and analyzing their understanding before and after technology-enhanced lessons fundamentally changed how I think about technology integration. I used to rely on my gut feeling about whether something worked. Now I systematically gather evidence (student artifacts, assessment data, observation notes) and let that evidence drive my decisions. When I thought my flipped classroom approach was working great, student data showed significant gaps in conceptual understanding. That evidence forced me to rethink my entire approach."

Collaborative problem-solving emerged as crucial for overcoming challenges and generating innovative solutions. An English teacher described:

"When I was struggling to make digital annotation tools work for close reading instruction, my action research team was invaluable. We brainstormed together, shared strategies, and one colleague demonstrated a completely different approach I hadn't considered. The collective intelligence of the group consistently produced better solutions than I could have developed alone. We challenged each other's assumptions, asked probing questions, and held each other accountable for focusing on student learning rather than technology for its own sake."

Regarding iterative refinement, a social studies teacher reflected:

"Power of action research wasn't in any single cycle but in the accumulation of learning across cycles. Each iteration built on previous insights. First cycle focused on basic functionality, can I make the technology work? Second cycle addressed engagement, are students interested? Third cycle targeted learning, are students actually developing deeper historical thinking? By the fourth cycle, I was fine-tuning details and addressing individual student needs. This progressive deepening couldn't have happened in a one-shot workshop."

The identification of systematic experimentation as a primary mechanism supports the premise that action research creates protected spaces for teachers to take pedagogical risks and learn from both successes and failures. Action research empowers teachers to systematically investigate their own practices and develop context-specific solutions (Mertler, 2017). A science teacher's experience with virtual laboratories illustrates how action research reframes failure as data rather than as professional inadequacy. This stands in contrast to traditional professional development models, in which teachers often feel pressure to implement technologies flawlessly (Lawless & Pellegrino, 2007). By embedding expectations for multiple iterative cycles, action research legitimized experimentation and reduced the anxiety and risk aversion frequently identified as barriers to technology integration (Bingimlas, 2009). Treating initial instructional attempts as hypotheses allowed teachers to cultivate resilience in navigating technology-enhanced teaching practices.

Evidence-based reflection emerged as the most frequently referenced mechanism, highlighting its central role in transforming teachers' technology integration from intuition-based practice to inquiry-driven decision-making. Professional expertise develops through the systematic examination of actions and their consequences (Schön, 1983). A mathematics teacher's shift from relying on "gut feelings" to analyzing student learning data illustrates the epistemological transformation fostered by action research. By positioning teachers as knowledge generators who validate their practices through systematic evidence collection, action research strengthens professional agency (McNiff & Whitehead, 2011). Structured reflection protocols created opportunities for teachers to critically examine underlying assumptions about the impact of technology on learning processes. Such evidence-based reflection is particularly important given that teachers' beliefs about technology often remain resistant to change without systematic inquiry (Ertmer et al., 2012).

Collaborative problem-solving and iterative refinement operated synergistically to create powerful professional learning environments. An English teacher's description reflects the amplifying effect of collaborative action research, in which diverse perspectives contribute to the generation of innovative solutions (Sagor, 2011). This finding is consistent with evidence that collaborative professional learning communities enhance teachers' capacity for effective technology integration (Admiraal et al., 2013). A social studies teacher's reflection further illustrates how iterative refinement supports progressively more sophisticated integration, representing what is characterized as genuine technological pedagogical competence (Koehler & Mishra, 2009). Each action research cycle built upon prior learning, producing a spiraling developmental trajectory from basic technical functionality toward deeper

pedagogical transformation, consistent with progression patterns described in the DigCompEdu framework (Redecker, 2017). The integration of collaboration and iteration created the conditions identified as essential for meaningful and sustained teacher change (Timperley et al., 2007).

2.4. Contextual Factors Influencing Action Research Effectiveness

Analysis of qualitative data revealed significant contextual factors that either facilitated or constrained the effectiveness of action research-based technology integration. Table 4 summarizes the key facilitating and constraining factors identified through thematic analysis, along with their frequency of occurrence across data sources.

Table 4. Contextual Factors Influencing Action Research Effectiveness: Frequency of Coded References

Factor Category	Specific Factor	Facilitating n	Constraining n	Total n
Leadership support	Administrative encouragement	78	12	90
	Time allocation for meetings	45	34	79
	Resource provision	52	28	80
School culture	Collaborative norms	68	15	83
	Innovation orientation	61	22	83
	Risk tolerance	44	31	75

Source: Primary data, 2025

The prominence of leadership support and collaborative school culture as facilitating factors raises critical questions about scalability and replicability of action research-based approaches to developing digital pedagogical competence. Findings suggest that this model's success is highly dependent on specific contextual conditions that cannot be assumed to exist in all settings. This dependency presents significant challenges for broader implementation. Without strong administrative support, action research-based professional development may be unsustainable.

Teachers consistently emphasized the importance of administrative support for creating conditions that enabled meaningful action research engagement. A mathematics teacher reflected:

"Our principal understood that this work required time, time to meet as a team, time to plan lessons, time to analyze data. She adjusted our schedules to provide common planning periods and protected that time from other demands. Without that structural support, we couldn't have sustained the collaborative inquiry. She also celebrated our work publicly, which signaled to the whole school that innovation and experimentation were valued."

Regarding school culture, a science teacher noted:

"In my school, there's a strong culture of collaboration where teachers regularly observe each other and share practices. This made the action research feel like a

natural extension of what we already do rather than something completely foreign. In contrast, a colleague from another school described a more isolationist culture where teachers rarely discuss instruction, and she found it much harder to engage her team in the collaborative aspects of action research."

Technical infrastructure challenges were frequently mentioned as constraints. An English teacher explained:

"We designed this brilliant lesson where students would collaborate on digital documents while conducting online research. When we implemented it, half the computers wouldn't connect to the Wi-Fi, the shared documents kept freezing, and students spent more time troubleshooting technology than actually learning. It was incredibly frustrating and almost derailed our action research completely. We had to modify our plans significantly to work around unreliable infrastructure."

Team dynamics, particularly psychological safety, were identified as critical for productive action research engagement. A social studies teacher described:

"The trust within our action research team was essential. We could admit when lessons bombed, share our uncertainties, and give each other honest feedback without fear of judgment. I was comfortable saying, 'I have no idea how to assess student learning in this virtual environment,' and my teammates helped me figure it out. In a less trusting group, I would have pretended to have all the answers and wouldn't have learned nearly as much."

Teacher self-efficacy evolved throughout the action research process, as one mathematics teacher reflected:

"Initially, my confidence with technology was low, and I seriously doubted whether I could successfully integrate digital tools into my teaching. But through the systematic action research process (small experiments, supportive feedback, evidence of student learning) my self-efficacy grew. By the end, I wasn't just implementing others' technology integration ideas; I was creating my own, sharing them with colleagues, and mentoring newer teachers. The action research process itself built the confidence I needed to persist through challenges."

The prominence of leadership support underscores the critical role administrators play in establishing organizational conditions that enable effective action research. Educational change requires supportive leadership that provides both resources and cultural permission for innovation (Fullan, 2016). A mathematics teacher's account of receiving protected time reflects essential features of effective professional development, including sustained duration, practice-embedded learning, and strong organizational support (Darling-Hammond et al., 2017). When administrative leaders recognize action research as legitimate professional work, they create the necessary time, space, and structural resources for sustained inquiry. This finding addresses the challenge that educational initiatives frequently fail when institutional contexts do not support ongoing collaborative investigation (Ross & Bruce, 2007). The contrast observed between collaborative and isolationist school cultures further demonstrates how existing institutional norms can either amplify or constrain technology integration efforts (Prestridge, 2012).

Technical infrastructure challenges reveal a persistent tension in educational technology implementation: the gap between pedagogical vision and technological reality. An English teacher's experience with recurring Wi-Fi failures reflects resource-related barriers that can undermine even well-designed technology initiatives (Hew & Brush, 2007). However, action research provided a structured framework that enabled teachers to adapt to contextual constraints rather than abandon technology integration efforts, thereby fostering professional

resilience. These findings suggest that teachers who develop digital pedagogical competence through action research are better equipped to function productively within imperfect technical environments. Although infrastructure challenges generated frustration, they did not inhibit competence development. This resilience may stem from action research's emphasis on systematic problem-solving, in which barriers are reframed as objects of inquiry rather than obstacles to progress (Mertler, 2017).

Team dynamics, particularly trust and psychological safety, emerged as foundational conditions for authentic professional learning. A social studies teacher's description of openly admitting uncertainty reflects essential elements of collaborative inquiry, including mutual respect, democratic participation, and collective commitment (Kemmis et al., 2014). This finding aligns with research on professional learning communities, which emphasizes that meaningful collaboration depends on the deliberate cultivation of trust and psychological safety that enables honest and critical examination of professional practice (Timperley et al., 2007). However, positive team dynamics did not emerge uniformly across all groups. Analysis revealed significant variation in how teams functioned. Two of four action research teams struggled with establishing psychological safety, particularly where hierarchical relationships between veteran and novice teachers persisted. One early-career teacher noted:

"I appreciated the idea of collaborative inquiry, but in practice, I often felt my ideas were dismissed or talked over by more experienced colleagues. There were times I held back from sharing struggles because I worried it would confirm their assumptions about new teachers not being ready for technology integration. The 'safe space' we were supposed to create felt more aspirational than real in our team."

This reveals crucial limitation in the success narrative: assumption that action research structures automatically generate relational conditions necessary for deep professional learning. When power dynamics remained unexamined, collaborative mechanisms could reinforce existing hierarchies (Cochran-Smith & Lytle, 2009). Evolution of teacher self-efficacy documented in mathematics teacher's reflection illustrates what Bandura's social cognitive theory would predict: efficacy beliefs strengthen through mastery experiences, social modeling, and supportive feedback, all embedded in collaborative action research.

Yet this development trajectory was neither universal nor linear. Self-reported efficacy gains must be interpreted with caution, as reliance on self-assessment introduces validity concerns. Teachers' perceptions may be influenced by social desirability bias, Dunning-Kruger effect, or response shift bias (Kruger & Dunning, 1999; Howard, 1980). Three participants who reported substantial efficacy gains simultaneously described persistent implementation struggles in journals, suggesting disconnect between perceived and demonstrated competence. One teacher wrote:

"I feel much more confident about technology integration now, and my survey responses reflect that growth. But honestly, when I'm actually in the classroom trying to manage 30 students with devices, I still panic sometimes. The gap between how I think about technology integration during our reflection meetings and what actually happens in my classroom is bigger than I'd like to admit."

This candid reflection underscores the complexity of self-reported data and highlights the need for triangulation with observational or artifact-based evidence (Desimone, 2009). Furthermore, this mechanism addresses self-efficacy barriers frequently identified as significant impediments to effective technology integration (Ertmer et al., 2012), suggesting that the systematic and inquiry-driven nature of action research may be particularly effective in strengthening teachers' professional confidence.

However, effectiveness appears contingent on favorable contextual conditions not universally present. For teachers in schools with inadequate infrastructure, unsupportive leadership, or excessive workload, action research created additional stress rather than

building efficacy. Two participants withdrew mid-year, citing inability to sustain the time and emotional investment required. One departing teacher explained:

"I believed in the value of action research, but I was drowning. Between teaching six classes, mandatory committee work, and trying to be present for my own family, I simply didn't have the capacity to engage thoughtfully with the reflection and planning cycles. The action research felt like one more thing piled on rather than professional learning that energized me. I felt I was failing at action research on top of everything else."

This withdrawal narrative complicates positive findings by highlighting that action research may inadvertently exclude or overwhelm teachers who most need professional support, those working under high-stress conditions with limited organizational resources (Avalos, 2011). Socially situated nature of professional learning means individual development cannot be divorced from working conditions, and when conditions are untenable, even well-designed professional development may fail.

Interplay between contextual supports and individual development highlights the socially situated nature of professional learning. Yet this interplay can create vicious cycles when conditions are unfavorable: inadequate support undermines engagement, which limits growth, which reinforces perceptions of technology integration as burdensome, which further reduces support. Predominantly positive findings reflect experiences of teachers who persisted in relatively supportive environments, but may not generalize to contexts where action research would face more substantial barriers. Readers should interpret these findings as illustrating action research's potential under favorable conditions rather than guarantees of success. Future research should explicitly examine action research implementation in high-needs schools with limited resources, skeptical leadership, and stressed teacher populations to understand whether mechanisms identified here operate (or fail to operate) in more challenging circumstances (Coburn, 2003).

Conclusion

This study demonstrates that action research-based technology integration serves as powerful and comprehensive approach to improving teachers' digital pedagogical competence, addressing critical gap between technology availability and meaningful pedagogical application. Significant improvements in all TPACK domains, particularly in the integrated knowledge areas (TPACK, TPK, and TCK) with effect sizes exceeding 1.4, provide evidence that iterative cycles effectively support teachers' development of complex competencies required for technology integration. Progressive advancement across all six DigCompEdu competence areas confirms that action research addresses multidimensional nature of digital pedagogical competence. The four identified mechanisms (systematic experimentation, evidence-based reflection, collaborative problem-solving, and iterative refinement) reveal how action research creates conditions for transformative professional learning moving teachers toward pedagogically meaningful integration aligned with curricular goals. While contextual factors such as leadership support, school culture, technical infrastructure, and team dynamics influence implementation effectiveness, action research demonstrates resilience in enabling teachers to develop competence even within imperfect conditions, fulfilling this study's objective of investigating how systematic inquiry can bridge the divide between technological potential and educational reality.

Based on findings, educational institutions should adopt action research-based professional development as primary strategy for building teachers' digital pedagogical competence, moving from traditional workshop models toward sustained, practice-embedded, collaborative inquiry extending across multiple cycles. School administrators must prioritize organizational conditions supporting action research engagement, including protected time for collaborative planning, flexible scheduling enabling team meetings, adequate technical infrastructure, and cultural norms legitimizing experimentation and learning from failure. Teacher education programs should incorporate action research methodologies and TPACK

framework principles into preparation and professional development, equipping educators with skills to systematically investigate and improve their technology integration practices. Policymakers should recognize that developing comprehensive digital pedagogical competence requires sustained investment in collaborative professional learning communities rather than one-time technology purchases or brief training, allocating resources to support multi-year action research initiatives with ongoing coaching and peer collaboration. Future research should examine long-term sustainability of competence developed through action research, investigate scalability across diverse educational contexts, and explore impact of teachers' enhanced digital competence on student learning outcomes and 21st century skills development.

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