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Professional Development in Digital Loop: Impact of ICT on Mathematics Teachers' Self-Efficacy and Practice

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Abstract

The integration of Information and Communication Technologies (ICT) in mathematics education has transformed teaching practices and reshaped models of teacher professional development (TPD). This systematic review examines the effects of ICT-based TPD on mathematics teachers' self-efficacy, technological pedagogical content knowledge (TPACK), and instructional practices, while identifying effective program features that foster digital competence and pedagogical innovation. This review analyzed thirty peer-reviewed studies published between 2018 and 2025 following the PRISMA framework, drawing data from Scopus, Web of Science, ERIC, SpringerLink, and ScienceDirect. Interventions included blended learning, GeoGebra-based training, MOOCs, and simulation-supported modeling. The findings reveal that ICT-integrated TPD enhances teachers' confidence, digital competence, and instructional creativity—especially when programs emphasize active learning, sustained mentoring, and collaborative professional communities. Persistent challenges remain, such as limited infrastructure, institutional barriers, and the digital divide that restrict large-scale implementation. Overall, the review underscores the need for context-responsive, scalable professional learning frameworks that balance technology, pedagogy, and content knowledge to advance mathematics teaching and learning in the digital age.

Keywords: GeoGebra, ICT, mathematics education, teacher professional development, TPACK

Introduction

Over the past few years, there have been significant changes in how mathematics is taught as a consequence of the introduction of Information and Communication Technologies (ICT) and the changing expectations of twenty-first-century learning environments. ICT allows dynamic visualization, simulation, interactivity, and individualized learning—opportunities that go far beyond the constraints of a conventional classroom. The use of GeoGebra, dynamic modeling tools, virtual simulations, MOOCs, and blended learning environments has transformed mathematics instruction and redefined expectations for teachers' competencies. Teachers in this digital age must not only command mathematical content but also integrate technology effectively into their pedagogy. Hence, the development of Technological Pedagogical Content Knowledge (TPACK) and pedagogical innovation within instructional design has become central to Teacher Professional Development (TPD) (Weigand et al., 2024; Quarder et al., 2025).

Contemporary TPD has shifted from isolated workshops to ongoing, collaborative, and technology-supported learning models. The use of online platforms and ICT tools offers teachers opportunities to co-design lessons, deepen conceptual understanding, and engage students through multimodal mathematical representations (Hidayat et al., 2024; Benning et al., 2023). Studies indicate that PD based on GeoGebra and simulations effectively enhances teachers' modeling abilities, visualization of abstract concepts, and students' problem-solving skills (Marange et al., 2025; Quarder et al., 2025). Moreover, blended learning and MOOCs provide scalable, flexible models that facilitate peer interaction and reflective learning (Hollebrands & Lee, 2020; Nührenbörger et al., 2025).

A significant factor influencing the success of ICT-based TPD is teacher self-efficacy—the belief in one's ability to plan and deliver effective instruction. Higher self-efficacy has been consistently linked with greater adoption of technology, pedagogical innovation, and long-term instructional improvement (Zhou et al., 2023; Bjerke & Xenofontos, 2024). Zhou et al. (2023), in a meta-analysis of 21 studies involving 1,412 teachers, reported a strong positive effect of ICT-based TPD on teacher self-efficacy ($g = 0.64$), with variations depending on program design and implementation. Self-efficacy develops gradually through pre-service preparation, mentoring, and continuous professional engagement (Bjerke & Xenofontos, 2024). TPACK development also shows a high correlation with digital self-efficacy, predicting teachers' ability to integrate technology effectively into mathematics teaching (Zeng et al., 2022; Quarder et al., 2025).

Empirical evidence further demonstrates that ICT-oriented TPD improves instructional methodology, fosters creativity, and enhances learning outcomes. Effective programs incorporate adaptive assessment, collaborative learning communities, and digital task design (Thurm & Barzel, 2020). Viberg et al. (2020) emphasize that teachers' personal interest and creative engagement are key determinants of successful technology integration. Yet, most research remains limited to specific tools or short-term contexts, leaving a gap in understanding the sustained impact of ICT-based TPD on classroom practice.

The advancement of technology and the global demand for digitally skilled teachers necessitate comprehensive evidence on the role of ICT in mathematics teacher development. This systematic review addresses that need by synthesizing 30 peer-reviewed studies published between 2018 and 2025. The review aims to examine the impact of ICT-oriented professional development on mathematics teachers' self-efficacy, TPACK, and instructional practices; to identify effective features and models of ICT-based TPD that foster pedagogical innovation and digital competence; and to analyze the barriers and enabling factors that shape the successful and sustainable implementation of ICT-integrated professional learning. Ultimately, this study seeks to inform how mathematics teachers can be empowered to become digitally capable, pedagogically creative, and adaptive to the evolving technological landscape of education.

Methods

This study employed a systematic review design guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to ensure methodological transparency and rigor. The review process followed the four stages of identification, screening, eligibility, and inclusion to maintain the integrity and reliability of the synthesis. A protocol developed in accordance with PRISMA guidelines defined the research scope, inclusion and exclusion criteria, search strategy, and data extraction process, minimizing potential bias and maintaining consistency throughout the review.

A comprehensive literature search was conducted in five major databases—Scopus, Web of Science, ERIC, SpringerLink, and ScienceDirect—to identify peer-reviewed journal articles published between 2018 and 2025. Boolean search strings were constructed using combinations of terms such as *ICT*, *GeoGebra*, *MOOCs*, *teacher professional development*, *TPD*, *mathematics teachers*, and *self-efficacy*. Manual screening of reference lists was also carried out to include additional relevant studies. Only empirical studies that focused on ICT-integrated professional development in mathematics education and examined teacher self-efficacy, Technological Pedagogical Content Knowledge (TPACK), or instructional practice were included. The abstracts which were not related to mathematics education, opinion pieces, and conference abstracts were excluded to ensure the validity of the final synthesis.

In total, 420 records were retrieved. After removing 40 duplicates and 280 screening abstracts, 100 full-text articles were assessed for eligibility. Final 30 studies were found to meet all criteria which were included in the final synthesis. A structured extraction matrix was then created to collect information on author, year, country, research design, ICT tools used, participant characteristics, and major findings. Data were tabulated in Microsoft Excel and analyzed qualitatively using a thematic approach in NVivo. Both deductive and inductive coding were applied—deductive codes derived from TPACK and Bandura's self-efficacy theory, and inductive codes from contextual patterns such as digital collaboration, adaptive assessment, mentoring, and institutional barriers. To enhance credibility, two independent reviewers coded all studies, with discrepancies resolved through discussion and consensus.

Thematic synthesis revealed six interrelated domains that captured the essence of ICT-based teacher professional development: TPACK enhancement through ICT integration, strengthening teacher self-efficacy, GeoGebra and simulation-based learning, MOOCs and blended learning, digital assessment and adaptive pedagogy, and barriers and enablers of ICT adoption. As the study was based entirely on secondary data from peer-reviewed sources, no ethical approval was required. Nevertheless, all research procedures adhered to principles of academic integrity, transparency, and proper citation.

Results and Discussion

This systematic review synthesized 30 peer-reviewed studies which were published between 2018 and 2025. The review then examined how ICT-oriented teacher professional development (TPD) influences mathematics teachers' self-efficacy, TPACK, instructional practices, and digital pedagogy. Following the PRISMA protocol, studies were selected from multiple international contexts and represented diverse methodological traditions, including qualitative, quantitative, and mixed-methods designs.

To provide an overview of the evidence base, Table 1 summarizes the 30 included studies, highlighting their research focus, methodological approaches, ICT tools used (e.g., GeoGebra, simulations, MOOCs, blended learning), and major outcomes relevant to teacher learning and classroom practice.

Table 1: Thematic areas and Evidence Summary of Representative Studies (2018–2025)

Themes	Core Focus / Description	Representative Studies	Evidence Summary
Development of TPACK for ICT Integration	PD programs enhancing integration of technological and pedagogical knowledge.	Hidayat et al. (2024); Quarder et al. (2025); Gerber et al. (2024); Zeng et al. (2022); Alsina et al. (2025); (2022); Kul (2018)	GeoGebra, simulations, and blended PD significantly improved teachers' TPACK and lesson-design capacity.
Strengthening Teacher Self-Efficacy	Growth of teachers' confidence and digital-teaching competence.	Zhou et al. (2023); Bjerke & Xenofontos (2024); Olawale & Hendricks (2024); Njiku et al. (2022); Nührenbörger et al. (2025)	ICT-based PD reported moderate-to-large effects ($g = 0.64$) on self-efficacy, especially when mentoring and collaboration were integral.
GeoGebra and Simulation-Based Learning	Dynamic software supporting modeling and visualization.	Marange & Tatira (2025); Benning et al. (2023); Siller et al. (2024); Gerber et al. (2024); Quarder et al. (2025)	Teachers developed stronger modeling and visualization skills, and students showed improved conceptual reasoning.
MOOCs and Blended Learning for Scalable TPD	Scalable PD combining online flexibility with peer interaction.	Hollebrands & Lee (2020); Nührenbörger et al. (2025); Attard & Holmes (2020); Dinçer (2025)	Blended formats outperformed online-only PD; peer discussion enhanced engagement and transfer to practice.
Digital Assessment and Adaptive Pedagogy	Technology-based feedback and formative assessment practices.	Vattøy & Gamlem (2025); Thurm & Barzel (2020); Muzsnay et al. (2025); Weigand et al. (2024)	Digital assessment training improved feedback literacy and promoted data-driven differentiation.
Barriers and Enablers of ICT Adoption	Institutional, infrastructural, and motivational influences on PD success.	Viberg et al. (2020); Bognar et al. (2024); Huang et al. (2024); Weinhandl et al. (2025); Amemasor et al. (2025)	Limited infrastructure, time constraints, and anxiety hinder ICT adoption, whereas administrative support and mentoring enable sustainability.

The thematic synthesis of these studies revealed six major themes that collectively explain how ICT-based TPD enhances mathematics teachers' capabilities and instructional quality.

Development of TPACK for ICT Integration

A strong and consistent finding across the reviewed studies is that ICT-based professional development is rather effective in enhancing the TPACK of mathematics teachers that can be associated with the technological equipment and the productive pedagogical methods. Teachers said that programs using GeoGebra, simulations, and modeling tasks would improve their theoretical, task-design, and intervention knowledge (Quarder et al., 2025). These data results correspond to the Mathematical Digital Competence to Teach (MDCT) framework (Weigand et al., 2024), that allows teachers to view oneself as the creators of the technology-oriented educational setting and not as active consumers of the digital technologies.

These findings align with broader international research demonstrating that digital tool training enhances teachers' capacity to design technology-rich instructional tasks and foster deeper conceptual engagement in mathematics classrooms.

Strengthening Teacher Self-Efficacy

Teacher self-efficacy emerged as a central construct strongly influenced by ICT-based TPD. A meta-analysis by Zhou et al. (2023), included in this review, reported a large effect size ($g = 0.64$) for ICT-integrated TPD on teachers' confidence to plan, implement, and evaluate digital instruction. Self-efficacy gains were highest in programs emphasizing active learning, hands-on experimentation, ongoing mentoring, and authentic classroom application (Bjerke & Xenofontos, 2024).

Several studies demonstrated that as teachers became more confident using ICT tools, they engaged more frequently in innovative pedagogies, risk-taking, and creative lesson design.

GeoGebra and Simulation-Based Learning

Simulation tools and GeoGebra appeared as strong agents of change in the teaching of mathematics. The reviewed studies showed that teachers who participated in GeoGebra-mediated professional development improved their skills in visualizing abstract concepts, designing exploratory learning tasks, and supporting mathematical reasoning in more dynamic ways (Marange & Tatira, 2025; Benning et al., 2023).

Similarly, simulation-based professional development helped teachers strengthen their technical fluency and engage in repeated cycles of reflection. Research reported that simulation environments encouraged teachers to practise, receive feedback, and refine their instructional approaches through continuous iterative processes (Siller et al., 2024; Galić et al., 2025).

Taken together, these studies suggest that technology-based modelling—through GeoGebra and simulation tools—supports teachers' self-efficacy and promotes more student-centred learning experiences in mathematics classrooms.

MOOCs and Blended Learning for Scalable TPD

The reviewed studies showed that MOOCs and blended learning models offered teachers flexible and scalable opportunities for professional development. Research indicated that when MOOCs were supported by peer discussion and feedback, teachers' pedagogical competence improved noticeably, whereas passive participation produced very little impact (Hollebrands & Lee, 2020). Similar findings from Attard and Holmes (2020) and Njiku et al. (2022) reported that blended learning models were more engaging, more sustainable, and more applicable to real classroom needs compared to fully online PD. These studies highlight the importance of hybrid TPD models that combine flexibility, collaboration, and contextual learning, enabling teachers to build skills in meaningful and sustained ways.

Digital Assessment and Adaptive Pedagogy

Across the reviewed literature, ICT-based professional development was found to strengthen teachers' abilities in digital assessment, automated feedback, and data-driven instruction. Studies reported that digital formative assessment enhanced teachers' capacity to guide personalized learning pathways (Vattøy & Gamlem, 2025), while adaptive assessment tools were shown to support more inclusive classroom practices (Thurm & Barzel, 2020). During the COVID-19 period, digital feedback systems also played a critical role in maintaining student engagement and continuity in hybrid settings (Huang et al., 2024). Overall, these findings suggest that technology-mediated PD provides teachers with stronger analytical and diagnostic skills, helping them implement adaptive pedagogy more effectively and responsively.

Barriers and Enablers of ICT Adoptation

Despite the evident benefits of ICT-based professional development, several systemic challenges continue to limit its widespread adoption. The reviewed studies pointed out barriers such as limited infrastructure, time constraints, digital anxiety, and lack of administrative support (Olawale & Hendricks, 2024; Huang et al., 2024). These constraints affected teachers' ability to fully integrate ICT into their instructional practices. At the same time, enabling conditions such as sustained mentoring, peer collaboration, and institutional investment were shown to support meaningful ICT integration in schools (Bognar et al., 2024; Amemasor et al., 2025). Evidence indicates that successful and long-term digital adoption becomes possible when ICT-based PD aligns with broader institutional structures that promote digital leadership and continuous learning.

Conclusion and Implications

This systematic review synthesized thirty peer-reviewed studies published between 2018 and 2025 that examined ICT-oriented teacher professional development (TPD) in mathematics education. The overall findings indicate that ICT-based TPD exerts a significant positive influence on teachers' technological pedagogical content knowledge (TPACK), self-efficacy, and instructional innovation. Effective programs consistently shared key characteristics such as active learning opportunities, sustained mentoring, collaborative teamwork, and adaptive assessment practices. These elements collectively contributed to deeper digital integration, strengthened pedagogical design, and more sustainable instructional change.

Drawing on the TPACK framework and Bandura's theory of self-efficacy, the review highlights how ICT-enriched professional learning builds teacher competence and confidence. When teachers participate in digital PD that includes modeling, simulation, and reflective feedback, they are better able to design technology-supported lessons and more assured in their ability to implement such strategies effectively. Despite these positive developments, however, persistent systemic constraints—such as limited infrastructure, unequal institutional resources, lack of ongoing technical support, and enduring digital disparities—continue to restrict the scalability and long-term sustainability of ICT-based TPD initiatives.

The implications of these findings point toward the need for stronger and more coordinated efforts at policy, institutional, and programmatic levels. For policy-makers, the results underscore the importance of developing supportive national and institutional environments that ensure equitable access to digital tools and improve technological infrastructure, particularly in underserved regions (Amemasor et al., 2025; Huang et al., 2024; Olawale & Hendricks, 2024). For teacher educators and program designers, pedagogically oriented ICT integration must remain a central priority. Frameworks such as TPACK and the Mathematical Digital Competence to Teach (MDCT) model (Weigand et al., 2024; Quarder et al., 2025) provide concrete guidance which align technology, pedagogy, and content in meaningful ways. Incorporating GeoGebra-mediated simulations, adaptive digital assessments, and MOOC-supported learning into TPD programs can further enhance teacher creativity, student engagement, and flexibility in instructional design (Marange & Tatira, 2025; Hollebrands & Lee, 2020).

From an institutional standpoint, school leaders play a crucial role in supporting teachers' digital development. Providing mentoring structures, peer-learning communities, and administrative backing can strengthen teachers' technological self-efficacy and encourage sustained pedagogical innovation (Benning et al., 2023; Bognar et al., 2024; Lee & Vongkulluksn, 2022). For researchers, the review points to the need for more longitudinal and comparative studies to understand the long-term effectiveness of ICT-based TPD. Future research should also test scalable and context-responsive models that account for variations in infrastructure, institutional culture, and local needs (Nuhrenborger et al., 2025; Hollebrands & Lee, 2020).

In sum, the evidence suggests that ICT-oriented TPD has considerable potential to transform mathematics instruction by strengthening teacher competence, promoting digital pedagogical innovation, and supporting more engaging and effective learning environments. Realizing this potential, however, requires collective commitment—from policy-makers, institutions, teacher educators, and researchers—to create enabling conditions that ensure equitable access, pedagogical alignment, and sustainable digital professional learning.

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