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Opportunities of Artificial Intelligence Technologies in Developing the Pedagogical Competencies of Primary School Mathematics Teachers

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Abstract: This study explores how Artificial Intelligence (AI) technologies can enhance the pedagogical competencies of primary school mathematics teachers. It examines the role of AI tools, including adaptive learning platforms, intelligent tutoring systems, learning analytics, and generative AI, in supporting lesson planning, differentiated instruction, formative assessment, and professional development. Grounded in the TPACK, AI-TPACK, and UNESCO AI Competency Framework for Teachers, the study highlights the opportunities and challenges of AI integration in mathematics education. The findings suggest that AI can significantly strengthen teachers' pedagogical competence when supported by adequate digital skills, institutional support, and ethical implementation. The study concludes that effective teacher training and responsible AI adoption are essential for maximizing the educational benefits of AI in primary mathematics instruction.

Keywords: Artificial intelligence; pedagogical competence; primary mathematics education; TPACK; AI-TPACK; teacher professional development; adaptive learning; intelligent tutoring systems.

Introduction: The rapid advancement of artificial intelligence (AI) has begun to reshape nearly every domain of contemporary education, and primary mathematics education is no exception. Mathematics, as a subject that relies heavily on the sequential mastery of concepts, individualized feedback, and continuous formative assessment, is particularly well suited to benefit from AI-based instructional tools such as adaptive learning platforms, intelligent tutoring systems, automated assessment engines, and generative AI assistants. At the same time, the effectiveness of any technology in the classroom depends less on the sophistication of the tool itself than on the competence of the teacher who mediates its use. Consequently, a growing body of research has shifted its focus from AI as a student-facing technology toward AI as an instrument for developing teachers' own pedagogical competencies.

Pedagogical competence, in this context, refers to the integrated set of knowledge, skills, and professional judgment that enables a teacher to plan, deliver, assess, and continuously improve instruction in response to learners' needs. For primary school mathematics teachers, this competence includes the ability to represent abstract mathematical concepts in age-appropriate, concrete forms, to diagnose individual misconceptions, to differentiate instruction for heterogeneous classrooms, and to use data to inform instructional decisions. AI technologies intersect with each of these dimensions, offering new means of lesson preparation, real-time diagnostic feedback, and personalized professional development.

The purpose of this article is to examine, on the basis of recent international scholarship, the specific opportunities that AI technologies create for developing the pedagogical competencies of primary school

mathematics teachers. The article addresses three research questions: (1) which categories of AI technology are most relevant to primary mathematics pedagogy; (2) through which theoretical mechanisms do these technologies contribute to teacher competency development; and (3) what conditions and risks determine whether this potential is realized in practice.

The Technological Pedagogical Content Knowledge (TPACK) framework, originally proposed by Mishra and Koehler (2006), remains the dominant theoretical lens through which researchers examine teachers' capacity to integrate technology into instruction. The framework conceptualizes effective technology-supported teaching as the dynamic intersection of technological, pedagogical, and content knowledge, rather than as three independent skill sets. Building on this foundation, Luo et al. (2025) argue that the rapid diffusion of AI in education has necessitated an explicit extension of TPACK into an "AI-TPACK" construct, which incorporates teachers' understanding of AI's technical logic, its pedagogical affordances, and its implications for subject-specific content delivery, including mathematics. This extension reflects the recognition that AI systems do not merely digitize existing instructional materials but actively reshape pedagogical decision-making through automated recommendation, adaptive sequencing, and predictive analytics.

Several large-scale empirical studies conducted among primary mathematics teachers provide converging evidence on the determinants of AI adoption. A mixed-methods study of 1,205 primary mathematics teachers in Southwest China found that teachers' TPACK and their attitudes toward AI were decisive predictors of successful AI integration, while external factors such as school infrastructure and parental involvement played a comparatively secondary role (ScienceDirect, 2025). A related quantitative study employing the Technology Acceptance Model in combination with TPACK similarly found that teacher attitudes exert a critical influence on AI utilization, and that the direct effect of TPACK on actual use is comparatively modest, operating largely through its indirect influence on attitudes and other mediating factors (Springer, IJSME, 2024). These findings imply that competency-development interventions cannot rely on technical training alone; they must also address teachers' beliefs, self-efficacy, and professional identity in relation to AI.

A case study from a southwestern Chinese city further situates these findings within an ecological systems perspective, showing that supportive external conditions — including coherent educational policy, adequate technological infrastructure, and active community engagement — significantly reinforce teachers' positive attitudes and enhance their competence in integrating digital technologies into mathematics instruction (Education and Information Technologies, 2025).

Beyond TPACK-based models, researchers have proposed dedicated frameworks for teachers' AI-related competencies. Fan, Wang, and Gu (2026) developed and validated a framework and measurement scale for what they term teachers' "data-artificial intelligent competence" (DAIC), defined as a composite capacity integrating data literacy, AI collaboration skills, and ethical judgment. Their work situates DAIC as a central bridge between technological innovation and teaching practice, consistent with international guidance describing a broader shift from technology-enabled teaching toward data- and AI-driven teaching. At the policy level, UNESCO's AI Competency Framework for Teachers (2024) offers the most comprehensive international reference point, defining fifteen competency blocks organized across five aspects — a human-centered mindset, ethics of AI, foundational AI knowledge, pedagogical application of AI, and AI-supported professional development — distributed across three progression levels of acquisition, deepening, and creation. This framework is directly applicable to primary mathematics teachers insofar as it links generic AI literacy with subject-specific pedagogical application, including task differentiation, generation of exemplars, and verification of AI-produced feedback.

Adaptive learning platforms allow primary mathematics teachers to move beyond one-size-fits-all lesson planning by generating differentiated tasks calibrated to individual students' readiness levels. A study focused on Fujian Province applied a hybrid neural-network model to analyze primary students' mathematics learning patterns, demonstrating that AI-based diagnostic tools can identify specific learning difficulties and generate individualized instructional support, thereby extending teachers' diagnostic competence beyond what manual

observation alone can achieve (PMC, 2022). For teachers, engaging with such systems cultivates a more analytic, evidence-based approach to lesson design, since instructional decisions become grounded in continuously updated performance data rather than static curricular sequencing alone.

AI-supported assessment tools, including automated marking systems and learning-analytics dashboards, provide primary mathematics teachers with real-time insight into class-wide and individual error patterns. This immediacy of feedback strengthens teachers' formative assessment competence by shifting their professional attention from the labor of computation and marking toward the higher-order tasks of interpreting error patterns and designing corrective instruction. The UNESCO framework explicitly identifies this capacity — generating draft feedback or success criteria with AI while independently verifying their pedagogical accuracy — as a core AI-supported teaching competency (UNESCO, 2024).

Generative AI assistants can support teachers' continuous professional development by helping to draft lesson plans, generate task variants at different levels of difficulty, and simulate student misconceptions for reflective analysis. Because such tools lower the time cost of producing differentiated materials, they create additional space for teachers to engage in professional reflection, peer collaboration, and targeted self-study — activities long recognized as central to pedagogical competence development, independent of any specific technology. UNESCO (2024) recommends that teachers select one or two AI-related competencies, such as prompt design or bias awareness, as concrete annual professional development goals, embedding AI literacy within existing cycles of teacher appraisal and growth.

Finally, the process of learning to use AI tools responsibly is itself a competency-building exercise. As Fan et al. (2026) argue, data-AI competence functions as a meta-competency that underlies effective use of any specific AI tool, encompassing the capacity to evaluate the reliability of AI-generated content, to recognize algorithmic bias, and to make ethically grounded decisions about when AI assistance is pedagogically appropriate for young mathematics learners. For primary teachers, whose students are highly dependent on adult mediation, this meta-competency is arguably more consequential than proficiency with any single application.

Despite these opportunities, the reviewed literature consistently identifies conditions under which AI's contribution to pedagogical competence development is constrained. First, teachers with low initial digital self-efficacy or negative attitudes toward AI tend to underutilize even well-designed tools, regardless of their technical sophistication (ScienceDirect, 2025; Springer, IJSME, 2024). Second, insufficient institutional infrastructure and the absence of sustained, subject-specific training programs limit teachers' ability to translate AI exposure into genuine pedagogical competence, rather than superficial tool operation (Education and Information Technologies, 2025). Third, over-reliance on AI-generated recommendations without independent professional verification risks eroding teachers' own diagnostic judgment, a concern explicitly addressed in UNESCO's emphasis on maintaining human agency and critically evaluating AI-produced feedback before it reaches learners (UNESCO, 2024). Finally, questions of data privacy, algorithmic bias, and the appropriateness of specific AI tools for young children require primary teachers to exercise a level of ethical judgment that current pre-service teacher education programs rarely address in adequate depth.

The convergence of findings across the reviewed studies suggests that AI technologies function less as an autonomous driver of pedagogical improvement and more as a catalyst whose effect is mediated by teachers' attitudes, institutional context, and access to targeted training. This has direct implications for teacher education policy in the context of primary mathematics instruction. First, pre-service and in-service training programs should integrate AI-TPACK development explicitly into their mathematics methods courses, rather than treating digital competence as a generic, subject-neutral module. Second, school administrations should provide structured opportunities for teachers to practice AI-supported lesson design and assessment under mentorship, allowing attitudinal barriers to be addressed alongside technical skill-building. Third, national and institutional policies should adopt internationally recognized reference points, such as the UNESCO AI Competency Framework for Teachers, to standardize expectations while allowing for context-

specific adaptation to local curricular and infrastructural conditions. Fourth, ethical and data-literacy components should be embedded from the earliest stages of teacher training, given the particular vulnerability of primary-age learners to poorly verified AI-generated content.

These recommendations are consistent with the broader international literature on AI in education, which cautions that technology adoption without corresponding investment in teacher competence tends to reproduce, rather than resolve, existing inequities in instructional quality (Zawacki-Richter et al., 2019; Holmes, Bialik, & Fadel, 2019). For primary mathematics education specifically, where conceptual foundations laid in early grades strongly influence later achievement, the stakes of getting this balance right are especially high.

This article has examined the opportunities that artificial intelligence technologies offer for developing the pedagogical competencies of primary school mathematics teachers, drawing on recent empirical and theoretical scholarship. The evidence indicates that AI-based adaptive learning platforms, intelligent diagnostic tools, learning-analytics systems, and generative AI assistants can meaningfully strengthen teachers' capacity for differentiated instruction, formative assessment, and reflective professional development, particularly when their use is grounded in frameworks such as AI-TPACK and the UNESCO AI Competency Framework for Teachers. At the same time, this potential is not self-executing: it is conditioned by teachers' attitudes and digital self-efficacy, the adequacy of institutional support and infrastructure, and the presence of explicit ethical and data-literacy training. Future research should prioritize longitudinal and classroom-based studies that trace how AI-supported competency development translates into measurable improvements in primary mathematics teaching quality and student learning outcomes, particularly in educational contexts beyond the East Asian settings that currently dominate the empirical literature.

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