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## The Impact of AI on Primary School Teachers' TPACK Transformation Challenges in the Chinese Education Context

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**Abstract.** Existing research on artificial intelligence (AI) in education largely relies on general technology adoption frameworks and higher education contexts, offering limited empirical insight into AI-driven TPACK transformation in primary schools. The study aims to examine how AI use influences the interactions among technological, pedagogical, and content knowledge (TPACK) of primary school teachers and to explore teachers' perceptions of the transformative and constraining effects of AI on pedagogical practice. A mixed-methods design was employed, combining a survey and semi-structured interviews. Survey data were collected from 500 primary school teachers across 50 schools that had implemented AI-supported instruction, while 50 teachers were purposively selected for in-depth interviews. Quantitative data were analyzed using descriptive statistics and regression; qualitative data were analyzed using thematic analysis. The survey findings indicated moderate to high levels of AI-driven TPACK, with AI-technological pedagogical knowledge emerging as the strongest predictor of integrated TPACK-AI transformation. The qualitative findings revealed that teachers perceive AI as enhancing lesson design, differentiation, and content representation, while also introducing pedagogical constraints related to ethical concerns, developmental appropriateness, and classroom management. This study extends the literature by empirically positioning AI not just as a tool to adopt, but as a pedagogical co-actor that shifts what counts as competent integration at the TPACK intersection, especially under primary-school constraints.

**Keywords:** assessment; Chinese education context; ethical concern; pedagogical transformation; TPACK-AI

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## 1. Introduction

The rapid advancement of artificial intelligence (AI) has significantly reshaped educational landscapes worldwide, introducing new possibilities and complexities for teaching and learning in primary education (Holmes et al., 2022; Luckin et al., 2022; Wong & Looi, 2024). As AI-driven tools increasingly support instructional planning, assessment, and personalized learning, primary school teachers are required to reconceptualize their professional knowledge beyond traditional pedagogical and content expertise (Arifani; 2019; Giannakos et al., 2024; Roll & Wylie, 2021). In this context, the technological pedagogical content knowledge (TPACK) framework provides a critical lens for understanding how teachers integrate emerging technologies, such as AI, into classroom practice by emphasizing the dynamic interaction among technological, pedagogical, and content knowledge (Celik, 2023; Mishra et al., 2023).

Pedagogical transformation and challenges in AI-supported primary education within the TPACK framework refer to changes in teaching practices that occur when teachers effectively integrate AI by aligning technological, pedagogical, and content knowledge (Mishra et al., 2023; Prilop et al., 2025). Pedagogical transformation involves teachers' ability to design developmentally appropriate, learner-centered instruction that uses AI to support personalization, formative assessment, and differentiated learning while maintaining curricular coherence (Ng et al., 2024; Zhai et al., 2022).

However, this transformation is constrained by challenges such as limited AI-related technological knowledge, difficulties in pedagogically aligning AI tools with subject content, ethical and data-privacy concerns, unequal access to technology, and the risk of over-reliance on AI that may reduce meaningful teacher-student interaction (Bergdahl & Sjöberg, 2025; Collie et al., 2024; Filiz et al., 2025). These challenges directly affect teachers' TPACK development and the quality of AI-enhanced teaching in primary education (Luckin et al., 2022; Zhou et al., 2025).

Despite the growing body of literature on the impact of AI in education, two critical research gaps remain evident in studies examining AI and teachers' TPACK transformation. First, a theoretical gap exists, as most prior research conceptualizes AI integration primarily through general technology adoption or digital competence frameworks, offering limited empirical insight into how AI specifically reshapes the dynamic interactions among technological, pedagogical, and content knowledge within the TPACK framework (Habibi et al., 2023; Scherer et al., 2021; Strzelecki, 2024). Consequently, the transformative and constraining mechanisms of AI on teachers' pedagogical practices remain under-theorized (Celik, 2023; Mishra et al., 2024).

Second, a contextual gap persists, as existing empirical evidence is predominantly derived from higher education settings, where learners' cognitive autonomy, institutional support, and technological infrastructure differ substantially from those in primary education (Labadze et al., 2023; Moorhouse, 2024; Suryanti et al., 2020). This reliance limits the generalizability of findings to primary school

contexts, where teaching requires developmentally appropriate pedagogy, stronger teacher mediation, and heightened ethical considerations (Ayanwale et al., 2022; Heine & König, 2025). Addressing these gaps is essential to advancing a more nuanced understanding of the AI-driven TPACK transformation challenges faced by primary school teachers (Wong & Looi, 2024).

The focus on primary education is theoretically and practically justified, as teachers at this level play a foundational role in shaping learners' cognitive development, digital literacy, and ethical awareness, making AI integration particularly sensitive and consequential. Accordingly, the research objectives are aligned with the identified problem by systematically examining (a) how AI use influences the interaction among TPACK components, (b) which AI-related competencies most strongly predict integrated TPACK transformation, and (c) what pedagogical and ethical challenges mediate this transformation in primary classrooms. Through this alignment, the study offers an original, context-sensitive contribution to the conceptual refinement and empirical operationalization of AI-driven TPACK in primary education.

## **2. Literature Review**

### **2.1 Theoretical framework of TPACK-AI**

The TPACK framework explains teachers' professional knowledge as a dynamic integration of Content Knowledge (CK), Pedagogical Knowledge (PK), and Technological Knowledge (TK), including their intersections (PCK, TCK, TPK) and the core synthesis (TPACK) needed for effective technology-integrated teaching (Mishra & Koehler, 2006). In the era of AI-enabled instruction, TPACK transformation can be understood as teachers' shifting capacity to redesign lessons, assessments, and classroom interactions by aligning what is taught (content), how it is taught (pedagogy), and which AI tools are used (technology), while maintaining developmentally appropriate practices for young learners. This transformation is not merely technical; it also requires teachers to interpret AI outputs pedagogically, evaluate appropriateness for children, and preserve professional judgment in decision-making (Bergdahl & Sjöberg, 2025; Filiz et al., 2025; Zhou et al., 2025).

Owing to the unique affordances of AI systems (e.g., automation, generative feedback, adaptive recommendations) and their associated risks (e.g., bias, privacy concerns), researchers are increasingly advocating for the inclusion of AI-specific, ethically grounded technology knowledge within TPACK. For example, work on AI-specific TPACK readiness highlights that teachers' ability to teach and integrate AI depends on AI-related forms of CK, PK, and TK, as well as on their interactions within the classroom (Yue et al., 2024). In addition, an ethical dimension is frequently emphasized in AI integration because teachers must evaluate the consequences of AI use for learners' data, fairness, and well-being – concerns that become especially salient in primary schooling, where students are minors, and learning is highly relational.

Accordingly, recent extensions of TPACK introduce new AI-focused dimensions that refine the meaning of TK in this context. One influential line is Intelligent-TPACK, which foregrounds teachers' professional knowledge to integrate AI

tools ethically and positions AI ethics as a critical knowledge domain alongside AI-related technological–pedagogical integration (Celik, 2023). Complementary work further links AI integration to AI literacy, commonly conceptualized as teachers' ability to (a) understand AI, (b) use or apply AI, (c) evaluate or create with AI, and (d) address ethical issues, providing an explicit competency base that can be embedded into TPACK constructs (Ng et al., 2021). Building on these perspectives, a practical TPACK-AI lens typically distinguishes AI-TK (knowledge of AI tools and how they function in practice), AI-TPK (how to teach with AI, prompting, orchestration, feedback use, monitoring errors), AI-TCK (how AI represents or reshapes subject content), and an AI ethics or governance dimension (privacy, bias, transparency, and responsible classroom use).

To examine primary school teachers' TPACK-AI transformation and challenges, these dimensions can be applied as an analytic frame for (a) mapping teachers' current practices (lesson planning, instruction, assessment) to AI-TK/AI-TPK/AI-TCK/AI ethics, and (b) identifying where transformation breaks down. For instance, challenges may appear as gaps in AI-TK (limited understanding of AI tool limits), misalignment in AI-TPK (difficulty converting AI outputs into child-appropriate pedagogy), weak AI-TCK (AI use that distorts core concepts or promotes superficial learning), or ethical constraints (privacy, bias, safeguarding) that inhibit adoption or reduce trust (Celik, 2023; Ng et al., 2021; Yue et al., 2024). In practical applications, transformation can be understood as changes in teachers' abilities, as reported or observed, across these areas. "Challenges" are seen as obstacles in each area (knowledge or skills), at the points where these areas intersect (integration difficulties), and in the ethics layer (risk management). This method provides a clear explanation of how AI impacts the TPACK framework in primary education.

## 2.2 TPACK Transformation

Recent studies on AI in education have largely operationalized AI integration through *general* technology-adoption logics (e.g., intention, usefulness, facilitating conditions) rather than through knowledge-in-practice models that can explain *how* teachers' instructional reasoning changes. For example, large-scale acceptance studies of ChatGPT in higher education primarily extend UTAUT/TAM-style predictors to explain students' use behavior, offering strong behavioral explanations but limited pedagogical theorization of classroom enactment (Habibi et al., 2023; Strzelecki, 2024).

Similarly, scholarship that maps broad promises or risks of generative AI often remains at the level of opportunities and challenges, without specifying mechanisms by which AI reconfigures teachers' pedagogical decision-making across subject matter, methods, and representations (Giannakos et al., 2024). This leaves a *theoretical gap*: AI is frequently treated as "another tool" in adoption or digital-competence trajectories, yielding limited empirical insight into how AI reshapes the dynamic interactions among technological, pedagogical, and content knowledge central to TPACK.

Within the last five years, several influential works explicitly argue that generative AI pressures a rethinking of TPACK, yet the evidence base still focuses on conceptual repositioning or measurement rather than on explaining the *transformative and constraining mechanisms* of AI in teachers' pedagogy. For instance, Intelligent-TPACK work advances AI-specific knowledge and ethics as important extensions. However, its primary contribution is scale/model development and correlational interplay among components rather than fine-grained theorization of how AI changes teachers' real-time orchestration of content, pedagogy, and technology (Celik, 2023).

Conceptual arguments similarly highlight how LLMs intensify questions of prompt design, epistemic vigilance, and the boundaries of technology knowledge, but they do not, on their own, deliver classroom-level empirical accounts of how AI shifts TPACK interactions during lesson design, instruction, and assessment cycles (Mishra et al., 2023). As a result, the field still under-theorizes *when and why* AI acts as an instructional amplifier (e.g., enabling rapid differentiation or feedback) rather than a constraint (e.g., narrowing the pedagogical repertoire through over-reliance, bias, or reduced epistemic agency) (Celik, 2023; Luckin et al., 2022).

Empirical work focusing on teachers' readiness, motivation, and self-efficacy provides valuable yet partial evidence for understanding AI's pedagogical implications. These studies often foreground psychological and contextual determinants rather than the TPACK micro dynamics of instructional knowledge integration. For example, research on beginning teachers' readiness for generative AI emphasizes preparedness and perceived capability in the "GenAI age." However, it typically does not trace how teachers' content representations and pedagogical strategies are redesigned through AI-mediated planning and enactment (Moorhouse, 2024).

Studies of teachers' motivation or engagement, or both to harness generative AI similarly illuminate occupational and contextual correlates, yet they stop short of specifying the mechanisms by which AI reorganizes teachers' pedagogical content reasoning and technology-mediated moves (Collie & Martin, 2024). Work on K-12 attitudes and AI self-efficacy shows variability by experience and support conditions, again offering limited explanatory power about *how* AI concretely alters the interplay among CK/PK/TK and their intersections in TPACK practice (Bergdahl & Sjöberg, 2025). Taken together, these findings strengthen the case that AI-related teacher learning cannot be reduced to "confidence" or "intention," and instead demands TPACK-grounded mechanistic accounts.

A second gap is strongly contextual: the empirical center of gravity remains higher education (students, preservice teachers, and faculty), which restricts what we can claim about primary-school teachers' AI-enabled TPACK transformations and constraints. The most-cited recent ChatGPT adoption evidence is explicitly situated in higher education learning contexts (Habibi et al., 2023; Strzelecki, 2024), while even teacher-education discussions of AI integration often emphasize curriculum-level considerations more than primary classroom contingencies (e.g.,

developmental appropriateness, safeguarding, parental expectations, and foundational literacy or numeracy pedagogy) (Ayanwale et al., 2022). Although K-12-oriented work is increasing, much of it still focuses on readiness, self-efficacy, and general integration rather than on primary-specific TPACK interactions and pedagogical constraints (Bergdahl & Sjöberg, 2025).

Consequently, a robust contextual gap persists we still lack sufficient primary-education evidence to theorize how AI specifically reshapes (or restricts) teachers' pedagogical practices through the TPACK framework, especially under the time, policy, and developmental constraints that uniquely characterize primary schooling. Based on the identified theoretical and contextual gaps, the following two research questions are proposed:

1. How does the use of AI influence the interactions among technological, pedagogical, and content knowledge (TPACK) of primary school teachers?
2. How do primary school teachers perceive the transformative and constraining effects of AI on their pedagogical practices within the TPACK framework?

### **3. Methodology**

#### **3.1 Design**

This study employed a mixed-methods research design that incorporated a quantitative survey and qualitative interviews to examine AI-driven TPACK transformation among primary school teachers comprehensively. The survey was conducted to address the first research question by quantitatively capturing patterns and relationships in how AI use influences the interactions among technological, pedagogical, and content knowledge within the TPACK framework across a broader teacher population. Semi-structured interviews were then subsequently conducted to address the second research question, enabling an in-depth exploration of teachers' perceptions of the transformative and constraining effects of AI on their pedagogical practices.

The complexity of AI justified the application of a mixed-methods approach; TPACK integration, which involved both measurable structural relationships and contextually embedded pedagogical experiences that could not be sufficiently explained by a single method alone. By combining quantitative generalizability with qualitative explanatory depth, this design allowed for triangulation and complementarity of findings, thereby strengthening the validity and interpretive richness of the study (Creswell & Plano Clark, 2018).

#### **3.2 Participants**

The participants were primary school teachers from 50 public primary schools in Mianyang City that had been implementing artificial intelligence (AI) to enhance teaching and learning processes, such as lesson planning, instructional delivery, assessment, and feedback. For the quantitative phase, 500 teachers (10 from each school) were recruited to complete the survey, ensuring broad representation across grade levels, subject areas, and teaching experience. This sample size was considered sufficient to examine patterns in AI use and its influence on the interactions among (TPACK). For the qualitative phase, 50 teachers were selected from the respondents using purposive random sampling criteria to participate in

semi-structured interviews. The selection criteria for interview participants were: (a) active use of AI tools in instructional practices, (b) variation in teaching experience (novice, mid-career, and senior teachers), (c) representation of different subject domains, and (d) diverse levels of self-reported TPACK-AI proficiency based on survey results. This purposeful selection enabled an in-depth exploration of teachers' experiences of AI integration within the TPACK framework, while ensuring rich contextual and pedagogical diversity.

### 3.3 Research Instrument

The questionnaire formulation process was grounded in the theoretical framework of TPACK-AI, which conceptualizes teachers' professional knowledge as the dynamic interaction among Technological Knowledge (TK), Pedagogical Knowledge (PK), Content Knowledge (CK), and their integrative domains (TPK, TCK, PCK, and TPACK) under AI-supported instructional contexts.

Drawing on recent extensions of TPACK for AI-enhanced teaching, the questionnaire was structured into five core dimensions: (a) AI-related Technological Knowledge (AI-TK), (b) Pedagogical Knowledge for AI-supported instruction (AI-PK), (c) Content-Specific AI Integration (AI-CK), (d) Integrated Pedagogical-Content-AI Knowledge (AI-PCK/AI-TPK), and (e) Overall TPACK-AI enactment in classroom practice. Each dimension consisted of four (4) items, yielding a total of 24, measured on a five-point Likert scale ranging from "Strongly disagree" to "Agree strongly". Item development was informed by prior validated TPACK instruments and recent AI-focused adaptations to ensure construct relevance and theoretical alignment (Celik, 2023; Mishra et al., 2023).

To establish content validity, the draft questionnaire was reviewed and validated by three experts with doctoral qualifications and peer-reviewed publications in educational technology, AI in education, and teacher professional development. The experts evaluated item clarity, theoretical representativeness, and contextual suitability for primary education. Based on their feedback, minor wording revisions and item realignments were conducted to enhance pedagogical specificity and developmental appropriateness. A pilot study was subsequently conducted with a sub-sample of primary school teachers to assess internal consistency reliability. The results indicated satisfactory reliability across dimensions, with Cronbach's alpha coefficients exceeding the recommended threshold of .70: AI-TK ( $\alpha = .86$ ), AI-PK ( $\alpha = .83$ ), AI-CK ( $\alpha = .79$ ), AI-TPK/PCK ( $\alpha = .88$ ), and overall TPACK-AI ( $\alpha = .91$ ), demonstrating strong internal consistency (Hair et al., 2022).

The interview protocol was developed in parallel with the survey instrument, drawing on the same TPACK-AI theoretical dimensions to ensure methodological coherence and complementarity. The qualitative protocol was designed to elicit teachers' lived experiences and interpretive meanings related to AI-driven pedagogical transformation and constraint, rather than to quantify competence. Accordingly, the interview guide was organized into four thematic categories: (a) AI use in lesson planning and content representation, (b) AI-mediated

pedagogical decision-making and classroom interaction, (c) perceived transformations in teacher roles and instructional practices, and (d) perceived constraints, ethical concerns, and contextual challenges in primary education. This structure aligns with qualitative recommendations for theory-informed yet flexible protocol design (Creswell & Poth, 2018).

Sample interview questions included: *“How has the use of AI changed the way you plan and represent subject content for young learners?”* *“Can you describe a situation where AI supported or constrained your pedagogical decisions in the classroom?”*, and *“How do you balance AI use with developmental and ethical considerations in primary teaching?”* The same panel of experts also reviewed the interview protocol to ensure theoretical alignment, age-appropriateness, and depth of inquiry. This expert-validated, theory-driven integration of survey and interview instruments strengthens construct validity and enables a robust mixed-methods examination of AI-driven TPACK transformation among primary school teachers (Creswell & Plano Clark, 2018).

### **3.4 Data Collection and Analysis**

Quantitative and qualitative data were collected sequentially using a mixed-methods design. Survey data were gathered first through a self-administered questionnaire distributed to primary school teachers across 50 schools in Mianyang City that had already implemented AI to support teaching and learning. The questionnaire was administered online to ensure accessibility and standardized administration, with participation being voluntary and anonymous. Upon completion of the survey, respondents were invited to indicate their willingness to participate in follow-up interviews. Based on predefined criteria (active AI use, variation in teaching experience and subject area, and diversity in TPACK-AI levels), 50 teachers were purposively selected for semi-structured interviews. Interviews were conducted individually, either face-to-face or via video conferencing, and were audio-recorded with participants' informed consent.

Survey data were analyzed using statistical software in several stages. First, descriptive statistics were computed to summarize teachers' AI use and TPACK-AI levels across dimensions. To address the first research question, inferential analyses through correlation and regression were employed to examine how AI use influenced the interactions among technological, pedagogical, and content knowledge. These analyses enabled the identification of significant relationships and the relative contribution of each TPACK-AI component to instructional transformation.

Interview data were transcribed verbatim and analyzed using thematic analysis to address the second research question. Analysis followed an iterative coding process, beginning with open coding to identify meaningful units related to AI use, pedagogical transformation, and constraints. These initial codes were then grouped into axial categories aligned with the TPACK-AI framework (e.g., changes in pedagogical decision-making, content representation, ethical concerns, and contextual constraints). Finally, selective coding was applied to develop

overarching themes that captured teachers' perceptions of AI's transformative and constraining effects in primary education. To enhance trustworthiness, data triangulation with survey findings and peer debriefing were employed, allowing qualitative insights to explain and enrich the quantitative results.

## 4. Results

### 4.1 Quantitative Findings

#### 4.1.1 The impacts of AI on primary school teachers' interaction among TPACK dimensions

The descriptive analysis revealed that primary school teachers demonstrated a moderate to high level of AI-driven TPACK across all dimensions. As shown in Table 1, the highest mean score was observed for AI-Technological Knowledge ( $M = 3.98$ ,  $SD = 0.61$ ). This was followed by AI-Technological Pedagogical Knowledge ( $M = 3.88$ ,  $SD = 0.63$ ) and AI-Pedagogical Knowledge ( $M = 3.85$ ,  $SD = 0.64$ ). In contrast, the Integrated TPACK-AI Transformation and Constraints dimension reported the lowest mean ( $M = 3.71$ ,  $SD = 0.69$ ).

**Table 1: Descriptive statistics and reliability of TPACK-AI dimensions**

Dimension	No. of Items	Mean	SD	Min	Max	Cronbach's $\alpha$
AI-Technological Knowledge (AI-TK)	4	3.98	0.61	2.10	5.00	0.86
AI-Pedagogical Knowledge (AI-PK)	4	3.85	0.64	2.00	5.00	0.84
AI-Content Knowledge (AI-CK)	4	3.76	0.67	1.90	5.00	0.81
AI-Technological Pedagogical Knowledge (AI-TPK)	4	3.88	0.63	2.10	5.00	0.87
AI-Pedagogical Content Knowledge (AI-PCK)	4	3.82	0.65	2.00	5.00	0.85
Integrated TPACK-AI Transformation & Constraints	4	3.71	0.69	1.80	5.00	0.88

**Table 2: Descriptive statistics of overall questionnaire scores**

Variable	Mean	SD	Skewness	Kurtosis
Overall TPACK-AI Score	3.83	0.58	-0.42	0.36

**Table 3: Regression analysis: Effects of AI domains on integrated TPACK-AI**

Predictor	$\beta$	SE	t	p
AI-Technological Knowledge (AI-TK)	0.21	0.04	5.25	< .001
AI-Pedagogical Knowledge (AI-PK)	0.26	0.05	5.78	< .001
AI-Content Knowledge (AI-CK)	0.18	0.04	4.62	< .001
AI-Technological Pedagogical Knowledge (AI-TPK)	0.29	0.05	6.11	< .001
AI-Pedagogical Content Knowledge (AI-PCK)	0.23	0.04	5.47	< .001

Model Fit	Value
R <sup>2</sup>	0.62
Adjusted R <sup>2</sup>	0.61
F	161.34
p (Model)	< .001

**Table 4: Summary of key quantitative findings**

Finding	Result
Teachers' overall TPACK-AI level	Moderate to high
Strongest predictor of transformation	AI-Technological Pedagogical Knowledge
Pedagogical constraints reported	Moderate (Mean = 3.71)
Model explanatory power	High (R <sup>2</sup> = 62%)

Reliability analysis indicated strong internal consistency for all questionnaire dimensions, with Cronbach's alpha coefficients ranging from .81 to .88, exceeding the commonly accepted threshold of .70. These results confirm that the measurement instrument was reliable for assessing AI-related TPACK constructs among a large sample of primary school teachers. Furthermore, the overall TPACK-AI score (M = 3.83, SD = 0.58) exhibited acceptable skewness and kurtosis values, suggesting that the data were approximately normally distributed and suitable for subsequent inferential analyses.

The regression analysis provided empirical evidence for the significant influence of AI-related knowledge domains on teachers' integrated TPACK-AI transformation. As presented in Table 3, all five predictor variables significantly contributed to the model ( $p < .001$ ), explaining 62% of the variance in integrated TPACK-AI transformation ( $R^2 = .62$ ). Among the predictors, AI-Technological Pedagogical Knowledge ( $\beta = .29$ ) emerged as the strongest determinant, highlighting the central role of teachers' ability to align AI tools with pedagogical strategies.

AI-Pedagogical Knowledge ( $\beta = .26$ ) and AI-Pedagogical Content Knowledge ( $\beta = .23$ ) also demonstrated substantial effects, underscoring the importance of pedagogical reasoning and content-sensitive instruction when integrating AI. Collectively, these findings suggest that AI-driven instructional transformation in primary education is not merely dependent on technological proficiency but is strongly shaped by teachers' pedagogical integration capabilities, thereby addressing the theoretical gap identified in prior AI adoption research.

## 4.2 Qualitative Findings

### 4.2.1 Primary school teachers' perception on the transformative and constraining effects of AI

Teachers widely perceived AI as transforming how they design lessons, particularly in planning efficiency, sequencing activities, and generating differentiated materials. Many described AI as a "co-designer" that supports pedagogical creativity while accelerating preparation time. As one teacher noted, "AI helps me redesign lessons faster without starting from zero" (T3). Others

emphasized instructional variety: *"I can generate multiple activity ideas for one topic and choose what fits my students best"* (T11); *"AI gives me alternative ways to explain concepts when students don't understand the first time"* (T19). Several participants highlighted adaptive planning: *"I now plan lessons with more flexibility because AI helps me adjust activities quickly"* (T27). However, this transformation was framed as pedagogical only when teachers retained decision-making control: *"AI supports my teaching, but I decide how the lesson runs"* (T42).

Participants consistently reported that AI improved how content was represented for young learners, especially through simplification, examples, and multimodal explanations. Teachers shared that *"AI helps me turn complex ideas into simple stories or examples"* (T6), while another stated, *"I use AI to generate examples that match students' daily lives"* (T14). Differentiation emerged strongly: *"For mixed-ability classes, AI helps me prepare different versions of the same material"* (T21). Teachers also valued scaffolding support: *"AI helps me anticipate where students might struggle"* (T33). However, teachers stressed the need for content checking: *"I always revise AI content to ensure it matches the curriculum and students' level"* (T45).

AI integration prompted a redefinition of teachers' professional roles – from sole knowledge providers to learning facilitators and mediators. Several teachers observed that *"My role has shifted to guiding students on how to learn with AI"* (T8). Others described increased orchestration demands: *"I need to manage how and when AI is used so students don't depend on it"* (T16). Teachers emphasized maintaining authority: *"AI doesn't replace my role; it changes how I support learning"* (T24). Some highlighted professional growth: *"AI pushes me to think more critically about my teaching strategies"* (T36). At the same time, teachers stressed responsibility: *"Students still look to me to judge what is right or wrong"* (T49).

Despite perceived benefits, teachers expressed concerns that AI could constrain pedagogical flexibility if used uncritically. Several noted that *"Sometimes AI suggestions limit my own teaching ideas"* (T5). Others warned of the risks of dependency: *"Students may rely too much on AI instead of thinking for themselves"* (T13). Time pressure also emerged: *"Checking AI-generated materials takes extra time"* (T22). Teachers described misalignment issues: *"Not all AI outputs suit primary students' cognitive levels"* (T31). These concerns led many to emphasize selective use: *"I only use AI when it truly supports my learning goals"* (T44).

## 5. Discussion

The discussion suggests that AI use is strengthening teachers' technological knowledge (TK) but does not automatically translate into coherent TPACK-level practice, because AI introduces *new* forms of technological mediation (e.g., prompting, evaluating model output, handling opacity or bias) that reconfigure how pedagogy and content are enacted in real time. This aligns with the Intelligent-TPACK argument that ethical, evaluative, and decision-making knowledge becomes part of teachers' professional knowledge for AI-based tools, not an add-on skill. In a primary-school context, the need for developmentally appropriate mediation means that AI-supported lesson design and feedback cycles may look effective at the TK layer while remaining fragile at

the TPK/TCK/TPACK layers, because teachers still have to align AI output with age-appropriate pedagogy, curricular sequencing, and misconceptions typical of younger learners (Adiyono et al., 2025; Celik, 2023).

Second, AI increases instructional *optionality* (more resources, faster planning, differentiated materials), but simultaneously increases the cognitive and ethical workload required to maintain pedagogical and content coherence (Filiz et al., 2025; Giannakos et al., 2024). Teachers' reports of both "transformative" and "constraining" effects mirror broader evidence that AI can boost efficiency and idea generation yet requires vigilant verification, calibration, and classroom management—especially when AI output is unstable or misaligned with learning goals (Ng et al., 2024; Prilop et al., 2025; Suryanti et al., 2022). This tension also explains why many studies still end up framed through *adoption/readiness* lenses rather than modelling the dynamic interaction among TK-PK-CK. Therefore, it is easier to measure use intention than to trace empirically how teachers' decisions shift across lesson phases (planning–enactment–assessment) inside TPACK.

Third, the results appear consistent with the growing evidence that teachers' AI self-efficacy and job conditions (time, support, leadership, policy clarity) shape whether AI becomes a genuine pedagogical amplifier or a source of constraint. Studies in K–12 and teacher work contexts show that perceived usefulness alone is insufficient. Variation in AI self-efficacy, resources, and institutional guidance predicts whether teachers integrate AI meaningfully or keep usage superficial or limited (Arifani et al., 2020; Ayanwale et al., 2022; Moorhouse, 2024). This is also where the constraints that were found (e.g., uncertainty about reliability, ethics, and appropriate scaffolding) fit prior GenAI research showing that educators often want clearer professional learning pathways and guardrails before embedding AI into instruction and assessment.

Fourth, compared with prior findings (which are still heavily higher-education-centric), the primary-school setting likely intensifies teacher mediation as the central TPACK hinge: younger learners typically require more structured scaffolding, closer monitoring, and stronger ethical protection (privacy, bias, age-appropriate content). This helps explain why transformative effects may cluster around planning and material generation, while constraining effects cluster around enactment (classroom control, ensuring understanding) and assessment (authenticity, fairness) (Yue et al., 2024; Zhou et al., 2025). This study therefore extends the literature by empirically positioning AI not just as a tool to adopt, but as a pedagogical co-actor that shifts what counts as competent integration at the TPACK intersection—especially under primary-school constraints.

Beyond statistical significance, the findings demonstrate clear practical significance for primary education by showing how AI-driven TPACK transformation directly informs classroom practice, lesson design, and instructional decision-making. The results indicate that AI-Technological Pedagogical Knowledge was the strongest predictor of integrated TPACK-AI development, suggesting that teachers' ability to mediate AI tools—rather than merely operate them pedagogically—substantially enhances differentiated instruction, formative feedback, and content representation for young learners.

In primary school contexts, where cognitive development, ethical guidance, and foundational literacy are central, the integration of AI was found to be most effective when teachers critically adapted AI outputs to align with developmental appropriateness. These findings provide actionable guidance for professional development programs, emphasizing not only technical AI skills but also pedagogical integration and ethical scaffolding tailored to primary classrooms.

Finally, teachers' attitudes toward AI to propose an explicit AI-driven TPACK interaction pathway for primary education: (a) AI raises TK rapidly (prompting, tool operation), (b) successful integration depends on teachers' capacity to translate AI affordances into TPK (scaffolding, orchestration) and TCK (curriculum-fit explanations or examples), and (c) constraints emerge when verification or ethics demands outpace available time, training, and policy support (Bergdahl & Sjöberg, 2025; Strzelecki, 2024). The field needs more TPACK-interaction evidence in K-12 contexts rather than continuing to rely on generalized adoption or digital competence models because those models do not adequately capture the "interactive work" teachers do to maintain pedagogy and content stability. At the same time, AI output is probabilistic and sometimes unreliable.

## **6. Conclusion**

This study concludes that the integration of artificial intelligence in primary education has generated moderate to high levels of AI-driven TPACK among teachers, with technological knowledge developing more rapidly than integrated pedagogical-content enactment. Quantitative findings demonstrate that AI-technological pedagogical knowledge is the strongest predictor of integrated TPACK-AI transformation. These findings imply that effective AI integration in primary schools depends not merely on access to AI tools but also on sustained professional development that strengthens teachers' capacity to mediate AI use pedagogically and ethically within the TPACK framework.

The study also contributes to understanding the nuanced role of AI in shaping teachers' pedagogical practices, emphasizing the importance of balancing technological advancements with pedagogical expertise to achieve effective, ethical, and developmentally appropriate educational outcomes. The study is limited by its cross-sectional design and reliance on self-reported data from a single city, which may constrain generalizability across broader educational contexts. Future research is therefore recommended to employ longitudinal and classroom-based observational designs across diverse regions to examine further how AI-driven TPACK evolves and to develop context-sensitive models of AI-supported pedagogy for primary education.

## **Conflict of Interest**

The authors declare that there is no conflict of interest regarding the publication of this article.

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