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Technological pedagogical readiness: Examining TPACK, educational ecosystem, and teacher attitudes in Chinese primary mathematics education

Mao Li [1*], Colleen Vale [2], Hazel Tan [2], Jo Blannin [2]

[1] Xinyang Normal University, CHINA
[2] Monash University, AUSTRALIA
***Corresponding Author:** mao.li@xynu.edu.cn

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ABSTRACT

This study examines the interrelationships among Educational Ecosystem Influences (EEI), Technological Pedagogical Content Knowledge (TPACK), and teachers' attitudes toward integrating technology in primary mathematics education. Utilizing a newly developed Technological Pedagogical Readiness (TPR) framework and a second-order structural equation model, the research analyses data from 554 primary mathematics teachers in China. The findings reveal significant connections between the educational ecosystem, TPACK, and teachers' attitudes, with EEI exerting a strong direct effect on TPACK ($\beta = 0.649$, $p < .001$) and both direct ($\beta = 0.417$, $p < .001$) and indirect effects on teachers' attitudes via TPACK (indirect $\beta = 0.237$, $p < .001$). TPACK also shows a significant positive association with teachers' attitudes toward technology integration ($\beta = 0.366$, $p < .001$), highlighting that supportive EEI enhances teachers' technological knowledge and their likelihood to integrate technology into teaching. The study underscores the importance of professional development, contextual supports, and parental and community involvement in fostering effective technology integration. Overall, the results indicate a partially mediated relationship between EEI and teachers' attitudes, with TPACK playing a central explanatory role. This study advances the understanding of technology integration in primary mathematics education in Asia, providing practical insights for educators, policymakers, and researchers to improve student learning in the digital age.

Keywords: TPACK, educational ecosystem influences, technology integration, teacher attitudes, primary mathematics education

INTRODUCTION

Technology integration in mathematics education has become a pivotal aspect of contemporary teaching practices, revolutionising how knowledge is imparted and absorbed (Blannin, 2022). In particular, mathematics education has been reshaped not only by digital tools but increasingly by artificial intelligence, including intelligent tutoring systems, adaptive practice engines, and generative-AI supports, which have changed students' learning and teachers' instructional design (Drijvers et al., 2018). Creatively utilizing these digital technologies has not only made abstract concepts more accessible but has also promoted an interactive and innovative learning environment (Thurm & Barzel, 2020). Teachers' knowledge, specifically their Technological Pedagogical Content Knowledge (TPACK), plays a crucial role in this process (Mishra & Koehler, 2006). TPACK refers to the integration of content knowledge, pedagogical knowledge, and technological knowledge, enabling teachers to design and implement technology-enhanced lessons that are both educationally sound and technically feasible (Niess, 2016). It is essential for teachers to possess a deep understanding of how technology can be leveraged to enhance student learning and how it interacts with the subject matter being taught.

Simultaneously, teachers' attitudes toward technology constitute a distinct yet interlocking determinant of integration. Building on the Technology Acceptance Model (TAM), attitudes are shaped by perceived usefulness and perceived ease of use, which in turn predict intentions and actual use (Davis et al., 1989; Gurer & Akkaya, 2022). In mathematics education, positive attitudes are associated with a greater propensity to experiment with digital representations and data-rich tasks, whereas negative attitudes can constrain uptake despite available infrastructure and knowledge (Hew & Brush, 2007; Klemer et al., 2024; Ottenbreit-Leftwich et al., 2010). Crucially, attitudes towards digital technologies do not form in isolation: They are influenced by teachers' TPACK (competence fosters confidence) and by the educational ecosystem: leadership support, targeted professional development, and students' technology literacy (Du et al., 2025; Li et al., 2025). Accordingly, teachers' attitudes toward digital

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technologies are foregrounded as a second focal construct, examined not in isolation but as part of a triadic model with teachers' TPACK and the broader instructional context.

The educational context, including factors like institutional support, technological infrastructure, and curriculum standards, plays a critical role in shaping the integration of technology in mathematics education, influencing educators’ knowledge, beliefs, attitudes towards technology, and intentions to use technological tools in the classroom (Ertmer & Ottenbreit-Leftwich, 2010). China presents a unique context due to its distinct educational system and policies, where primary mathematics is commonly taught by subject-specialist teachers. This arrangement significantly influences teachers’ professional learning, the development of their TPACK, and their attitudes toward technology integration. Since 2013, the Chinese government has made significant investments in educational technology, which, as Li (2023) noted, has led to a substantial increase in the proportion of primary schools in mainland China meeting the standards for laboratory instruments in mathematics, rising from 54.19% to 95.96% from 2013 to 2020. In other words, by 2020, most primary schools in China were well-equipped with the necessary resources for mathematics instruction, including computers, experimental mathematics tools, interactive whiteboards, and projectors. However, China’s unique cultural, social, and economic context necessitates a tailored approach to technology integration that considers the specific needs and challenges teachers and students face in this setting (Sang et al., 2011). This context raises pivotal questions essential to understanding the technology integration in China’s educational landscape. For example, what is the relationship between mathematics teachers’ TPACK and their attitudes toward integrating digital technology in teaching and learning? In the post-pandemic era, how does the current educational context shape mathematics teachers’ knowledge of and attitudes towards technology integration? Moreover, as AI becomes embedded in classroom practice, how do teachers perceive and appropriate AI-enabled tools (e.g., intelligent tutoring systems, adaptive platforms, generative-AI assistants), and how are these perceptions related to their TPACK and attitudes? Despite recent advancements and the release of AI Plus policies (State Council of the People’s Republic of China, 2025), a significant research gap remains in understanding the complex interplay among teachers’ TPACK, their attitudes toward technology integration, the educational context, and the emerging role of AI in China’s post-pandemic landscape.

Currently, much of the research on technology integration in education is concentrated on two main areas:

1) The technical aspects of implementation, such as the deployment and maintenance of hardware and software, and
2) The theoretical frameworks that guide its use, like TPACK (Mishra & Koehler, 2006) or Substitution Augmentation Modification Redefinition models (Hamilton et al., 2016).

Research on educational technology encompasses multiple dimensions, including the widespread adoption of established frameworks such as TPACK, TAM, and the Unified Theory of Acceptance and Use of Technology (Davis et al., 1989; Mishra & Koehler, 2006; Venkatesh et al., 2003). These models explain technology uptake through key constructs such as Technology-related knowledge, perceived usefulness and ease of use, performance and effort expectancies, social influence, and facilitating conditions. For instance, studies might examine the effectiveness of specific educational software in enhancing mathematics skills or analyse how teachers’ adoption of the TPACK framework influences their integration of digital tools in lesson planning. However, there is a lack of comprehensive studies that holistically consider teachers’ TPACK, their attitudes towards technology, and the educational context in which they operate. This gap limits educators’ understanding of how these factors interact and influence each other, thus hindering the effective integration of technology into classroom practices. China’s distinct educational system, emphasising high-stakes examinations and rigorous academic standards, creates a unique environment for technology integration (Sang et al., 2018). Understanding how teachers’ TPACK and attitudes towards technology intersect with this context can provide valuable insights for improving technology integration in primary mathematics education (Honey, 2018). By filling the existing research gap, educators can better understand how to effectively integrate technology into primary mathematics education in China. This knowledge can inform teacher professional development, educational policies, and classroom practices, ultimately improving student learning outcomes in mathematics. Importantly, the insights gained from this study may have broader applicability, informing technology integration efforts in other educational settings and contexts.

Research on educational technology is diverse and evolving, encompassing among many strands the design and evaluation of digital/AI tools (Canonigo, 2024; Du et al., 2025), studies of teacher learning and professional development (Tan & Yuan, 2024; Thurm et al., 2024), and work with pedagogical frameworks such as TPACK and TAM (Khong et al., 2023; Mailizar et al., 2021). However, relatively few studies jointly examine teachers’ technological–pedagogical knowledge, their attitudes toward technology, and the context in which they teach: An omission that obscures how these factors interact to shape classroom practice. This integrative gap is especially salient in China’s high-stakes, exam-driven system, where institutional demands and resource environments condition technology use in primary mathematics (Sang et al., 2018). Addressing this gap is essential for designing context-sensitive professional development, policies, and school supports that can improve teaching and learning.

In this study, these contextual influences are conceptualized as educational ecosystem influences (EEI): a multi-level construct comprising professional development, school leadership, policies, and resourcing, accountability pressures (e.g., high-stakes testing), students’ technology literacy, and parent–community involvement. Whereas “context” is a broad label and UTAUT’s facilitating conditions focus on perceived access/support, EEI captures broader social–organizational forces that condition classroom technology use in primary mathematics.

RQ1 What are the interrelationships between primary mathematics teachers’ TPACK, EEI, and attitudes towards technology integration in Chinese education?

LITERATURE REVIEW

Interplay of TPACK Constructs and Teacher Attitudes in Technology Integration

Previous research has delved into the intricate relationships among the seven TPACK constructs, providing substantial insights into how these components interact within the framework. One of the most widely discussed studies in this area is by Voogt et al. (2013), who offer a comprehensive review of the TPACK framework, critically examining how each of the seven constructs contributes to the holistic understanding of technology integration in education. They conclude that while individual constructs of TPACK are crucial, interaction among them is essential for effective technology integration in teaching. This interaction suggests that teachers' ability to integrate technology depends not solely on their knowledge of technology, content, and pedagogy in isolation but on their ability to synthesise these forms of knowledge in practice (Koehler et al., 2013; Niess, 2016; Schmidt et al., 2009). Following Voogt et al.'s (2013) comprehensive review, some subsequent researchers have employed structural equation modelling to statistically validate and investigate the internal structure of TPACK, further enriching educators' understanding of how these constructs interrelate in educational contexts. For example, Dong et al. (2015) conducted their research with 390 pre-service and 394 in-service teachers in Beijing, China. They found that except content knowledge (CK), pedagogical knowledge (PK), and pedagogical content knowledge (PCK), teachers' technological knowledge (TK), technological content knowledge (TCK), and technological pedagogical knowledge (TPK) had a direct and significant impact on their TPACK, indicating the essential interplay of these knowledge domains in enhancing teachers' competency to integrate technology effectively in educational settings (Dong et al., 2015). Similarly, Chai et al. (2011) investigated 834 pre-service primary school teachers' TPACK at a teachers' college in Singapore. They found that technology-related factors such as TK and TPK significantly influenced teachers' TPACK. These studies affirm that technology-related factors significantly shape teachers' TPACK, crucial for effective technology integration in education (Mishra et al., 2023; Yang et al., 2025).

Building on previous studies on the TPACK framework, researchers like Yang et al. (2019) delve into how TPACK influences teachers' attitudes toward technological adoption, using the TAM framework to highlight pedagogical knowledge's key role in embracing technology. Their study, involving 1,185 teachers across 45 primary and secondary schools in China, demonstrates that TPACK significantly shapes teachers' perceptions of technology's usefulness and ease of use, enhancing their willingness to integrate technology into teaching practices. This finding emphasises TPACK's essential role in promoting technology integration within China's educational landscape, suggesting that deep integration of technological understanding with pedagogical and content knowledge is crucial for fostering positive attitudes toward technology use in classrooms. Similarly, Khong et al. (2023) extended this line of research to the Vietnamese context, working with 1,740 secondary school teachers to explore how their TPACK influences their readiness to adopt technology. Their findings reinforce the critical role of TPACK in shaping educators' attitudes towards technology, showing consistency with the trends observed in China (Yang et al., 2019). These results underscore the universality of TPACK's impact across diverse educational settings, highlighting its significance in various cultural and educational contexts.

Moreover, the research by Marbán and Sintema (2021) and Tondeur et al. (2019) further expands our understanding of TPACK's influence on technology integration. Marbán and Sintema's study, conducted with 166 pre-service primary teachers at the University of Valladolid in Spain, explores how these educators perceive and integrate technology, offering insights into the European context (Marbán & Sintema, 2021). On the other hand, Tondeur et al. (2019) provided a broader international perspective, examining educators across various regions and educational levels, thus offering comprehensive insights into the global applicability of the TPACK framework. These studies collectively emphasise the crucial need to delve deeper into the relationship between educators' TPACK and their attitudes toward technology, underlining the significance of this interplay in enhancing the effective integration of technology across global educational landscapes and fostering positive technological adoption in different teaching environments (Li et al., 2025; Sun et al., 2024).

From "Contextual Factors" to EEI

The integration of technology in education is significantly affected by contextual factors that go beyond the scope of individual teacher competencies or technological resources (Mishra et al., 2023). Ertmer and Ottenbreit-Leftwich (2010) emphasise that both first-order barriers (external factors such as access to resources and training) and second-order barriers (internal factors including teachers' beliefs and attitudes) play crucial roles in technology integration. In mathematics education, these barriers can dictate the extent to which technology is utilised to facilitate learning and teaching. In line with these distinctions, key contextual factors identified in the literature include school leadership and vision, the availability of technical support, the culture of the school regarding innovation and technology use, teacher collaboration networks, and the alignment of technology use with curriculum standards and assessments (Hew & Brush, 2007; Li et al., 2025; Porras-Hernández & Salinas-Amescua, 2013; Zhao & Frank, 2003).

Also, some researchers pointed out that in some cultures, a high value placed on traditional teacher-centred methods may inhibit the adoption of digital technology, which often promotes student-centred learning environments (Tondeur et al., 2017). Hence, Polly (2024) argued that a school's culture that fosters innovation and risk-taking can significantly enhance technology integration in mathematics education, encouraging teachers to explore new teaching methods and digital tools. Additionally, the availability of infrastructure and resources can vary widely between schools with different economic statuses, impacting the degree to which digital technology can be integrated into mathematics education (Mukuka et al., 2021). Comparative studies, such as those by Law et al. (2008) and Porras-Hernández and Salinas-Amescua (2013), illustrate how educational technology integration is contextual and can vary significantly between countries and within regions, influenced by local educational policies, cultural values, and socioeconomic conditions.

Such variations highlight the necessity of a contextualised approach to understanding and enhancing technology integration in mathematics education, recognising that strategies successful in one setting may not be directly transferable to another. Therefore, the influence of contextual factors on technology integration in mathematics education is complex and dynamic. Understanding the compounding effects of factors is essential for developing effective strategies that accommodate different educational settings' specific needs and conditions. Recognising these influences, we can redefine these variables as the tendrils of the EEI, which interweave to either facilitate or hinder technology integration in mathematics education. Recognizing the interdependence of these factors clarifies the complexity and calls for tailored, context-sensitive approaches that respect the distinctive educational landscapes in which technology integration occurs.

Unveiling the Interplay: TPACK, Attitudes, and Context in Mathematics Education

The synthesis of the existing literature reveals a notable research gap in exploring the interplay between TPACK, attitudes towards technology integration, and contextual factors within the domain of mathematics education. While individual studies have delved into aspects of TPACK and attitudes towards technology (Li, 2023; Stein et al., 2019; Voogt et al., 2013; Yang et al., 2019), and others have considered the impact of contextual factors on educational technology integration (Ertmer & Ottenbreit-Leftwich, 2010; Hew & Brush, 2007; Mishra, 2019; Rehman et al., 2025), there is a lack of research that examines these elements in conjunction with the specific context of mathematics education.

Understanding the intricate relationship between TPACK, teachers' attitudes towards technology, and the myriad of contextual factors is paramount for several reasons. Firstly, it acknowledges that technology integration in mathematics education is not solely an outcome of teacher knowledge or attitudes but is also significantly influenced by external environmental factors (Mishra, 2019; Rehman et al., 2025; Zhao & Frank, 2003). Secondly, such comprehensive understanding aids in developing more effective professional development programs and educational strategies that address the internal competencies and external circumstances influencing teachers' technology integration practices (Polly, 2024; Tondeur et al., 2017). Third, a nuanced examination of how teachers' knowledge (TPACK), attitudes, and contextual conditions interact provides the conceptual and empirical groundwork for responsibly leveraging AI in primary mathematics—clarifying when, for whom, and under what conditions AI-supported tools are appropriate—rather than adopting them in a technology-driven manner. Given the evolving landscape of educational technology, particularly in the aftermath of the COVID-19 pandemic, such research could offer valuable insights for adapting to new educational challenges and opportunities. Accordingly, examining the intersection of TPACK, teacher attitudes, and contextual factors in mathematics education, which represents a gap addressed by this study, is crucial for advancing theoretical understanding of technology integration and for offering practical guidance to educators, policymakers, and other stakeholders aiming to optimize the role of technology in educational settings.

METHODOLOGY

Research Design

This study constitutes the quantitative phase of a mixed-methods project examining factors that influence primary mathematics teachers' technology integration in the post-pandemic era. Building on the qualitative phase that identified and theorised 11 factors and proposed the Technological Pedagogical Readiness (TPR) framework (Li et al., 2025), and on a separate paper that validated the TPR instrument (Li et al., 2024), the present phase tests the interrelationships among these constructs and their effects on technology integration. Data were collected through an online questionnaire, which was selected due to its efficiency, cost-effectiveness, standardized administration, and ability to reach a geographically diverse population of teachers while maintaining anonymity (Cohen et al., 2018). These characteristics enhance the feasibility of data collection and help alleviate concerns related to evaluation apprehension among school-based participants (Fowler, 2013). A second-order structural equation model (SEM) was employed because the focal constructs are hierarchical and latent (EEI, TPACK, Attitude), requiring simultaneous estimation of measurement and structural components, explicit treatment of measurement error, and formal testing of direct and mediated pathways (e.g., EEI → TPACK → Attitude) (Byrne, 2016; Kline, 2023). Second-order SEM was used, rather than regression on summed/averaged scale scores, because it is better aligned with theory, preserves the multidimensional structure of the constructs, explicitly models measurement error, and yields less biased estimates of relations among latent factors; accordingly, this approach suits the sample (N = 554) and research questions about hierarchical structure and mediated effects (Byrne, 2016; Hair et al., 2018).

Participants

In this study, the participants comprised primary mathematics teachers from 46 schools in Chongqing, China, representing a diverse cross-section of educators across grades one through six. The sample was 73.3% female teachers (n = 406) and 26.7% male teachers (n = 148), a distribution that mirrors the predominance of women in China's primary teaching workforce. Grade-level representation was balanced (14.8%–18.4% per grade), ensuring coverage of curricular expectations and technology uses from early numeracy to upper-primary mathematics. Teaching experience was varied: 16.1% had 0–5 years, 31.4% had 6–10 years, 19.3% had 11–15 years, and 33.2% had more than 15 years, yielding a mix of novice and veteran teachers who have encountered different policy cycles and post-pandemic technology initiatives. Together, this cohort, comprising multiple schools, balanced across grade levels, and diverse in teaching experience, provides the necessary heterogeneity to detect variability in the 11 constructs of interest. It also supports a robust estimation of the second-order SEM by minimizing single-context bias and enhancing the generalizability and interpretability of findings within the domain of primary mathematics education.

Table 1. Survey instrument information adapted from Li et al. (2024)

Construct	Number of items	Example item
Technological Pedagogical Content Knowledge (TPACK)	4	I can effectively integrate digital technology, mathematics knowledge and teaching methods in online mathematics classes.
Technological Pedagogical Knowledge (TPK)	3	I can guide students to engage in online collaborative learning.
Technological Content Knowledge (TCK)	3	I can use digital technology to conduct in-depth analyses of homework data and adjust teaching content accordingly.
Perceived Usefulness (PU)	4	Using digital technology in my mathematics teaching enables me to effectively achieve instructional objectives.
Perceived Ease of Use (PEoU)	4	In mathematics class, I prefer to use digital technologies that can be quickly mastered.
Technological Knowledge (TK)	5	AI tools can assist me in enhancing the effectiveness of my instruction.
Professional Development (PD)	4	The national teacher professional development programs help me to master various educational digital technologies.
Contextual Factors (CF)	5	School leadership support enhances my confidence in integrating digital technologies in the classroom.
Educational Challenges (EC)	6	Working with fellow teachers is an important method to address the problems of integrating digital technology into classroom instruction.
Students' Technology Literacy (STL)	5	My students can use digital resources to enhance their mathematics problem-solving skills.
Parental and Community Involvement (PCI)	4	Parents' information technology skills are essential for creating an effective educational environment.

Note. EC captures teachers' perceptions of instructional and systemic constraints in technology integration and their perceived ways of addressing these challenges (e.g., through collaboration), rather than challenges in isolation

Instrument

This study employed the TPR scale to operationalise the 11 constructs shaping primary mathematics teachers' technology integration (Li et al., 2024). The instrument was administered in Chinese using a five-point Likert scale (1 = strongly disagree, 5 = strongly agree), with higher scores indicating stronger readiness on each construct. In the structural equation model, all first-order constructs were specified as reflective, and the three higher-order constructs (TPACK, Attitude, and EEI) were modeled as reflective–reflective.

Although the TPR scale was previously developed and validated (Li et al., 2024), its psychometric performance was re-examined in the current sample (N = 554) to ensure adequacy for the present analysis. Confirmatory factor analysis indicated excellent model fit (χ^2/df = 1.111, RMSEA = 0.014, SRMR = 0.027, CFI = 0.993, TLI = 0.992), supporting the proposed measurement structure. Composite reliability values ranged from 0.840 to 0.917, exceeding the recommended threshold of 0.70, while Average Variance Extracted (AVE) values ranged from 0.623 to 0.670, demonstrating satisfactory convergent validity. Discriminant validity was established using the Fornell–Larcker criterion: For all constructs, the square root of AVE exceeded the corresponding inter-construct correlations.

These results confirm that the TPR scale demonstrates strong reliability and construct validity in this sample, providing a sound measurement foundation for subsequent second-order SEM analyses. Representative items are reported in **Table 1**; the full item set is available in Li et al. (2024).

Data Collection

Data were gathered via an online questionnaire administered to approximately 1000 primary mathematics teachers, resulting in 554 valid responses (response rate $\approx$ 55%). The survey targeted teachers across 46 public primary schools in Chongqing, China, covering Grades 1–6. All participating schools were public institutions located in urban districts, reflecting the dominant school type in the study region.

A stratified sampling framework was adopted to enhance sample diversity. With the assistance of the Chongqing Education Commission, schools were selected to ensure variation within the region, and all mathematics teachers within participating schools were invited to respond. Although formal stratification variables were not imposed at the individual level, the final sample exhibits substantial heterogeneity in gender, age, teaching experience, and educational background, consistent with the intended stratified design. Randomisation was operationalised through open invitation within selected schools rather than individual-level random assignment, which is common in large-scale, school-mediated survey research (Fowler, 2013).

The survey link was disseminated through WeChat, a platform widely used by Chinese educators, with distribution support from the Chongqing Education Commission to ensure institutional legitimacy and broad reach. The questionnaire was hosted on Qualtrics XM to enable secure data capture, mobile-friendly delivery, Chinese localisation, and basic branching/skip logic. Participation was voluntary and preceded by informed consent outlining the study purpose, procedures, and participant rights, in line with established ethical guidance (Cohen et al., 2018). Ethical approval for this study was granted by the Monash University Human Research Ethics Committee (Low Risk) (Project ID: 35148). The committee confirmed that the study met the requirements of the National Statement on Ethical Conduct in Human Research. The survey remained open for approximately two months, enabling teachers to participate at their convenience. This approach is associated with enhanced response quality in self-administered online surveys (Fowler, 2013). All data were analysed in aggregate, and no individual teacher or school is identifiable in reporting.

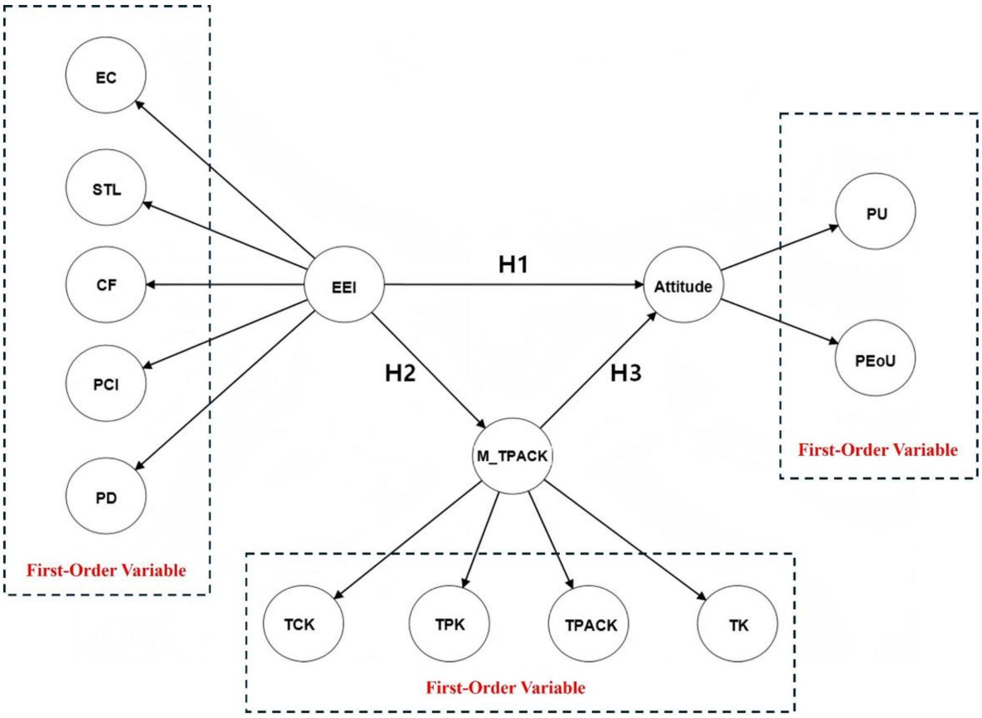

Figure 1. Second-order SEM of hypothesized relationships (H1–H3) (Source: Authors' own elaboration)
Note. EEI = Educational Ecosystem Influences; PD = Professional Development; CF = Contextual Factors; EC = Educational Challenges; PCI = Parental and Community Involvement; STL = Students' Technology Literacy; M-TPACK = Mathematics Teachers' Technological Pedagogical and Content Knowledge; TCK = Technological Content Knowledge; TPK = Technological Pedagogical Knowledge; TK = Technological Knowledge; Attitude is indicated by PU and PEoU; PU = Perceived Usefulness; PEoU = Perceived Ease of Use. Arrows depict hypothesized paths (H1–H3); dashed boxes group first-order indicators

Data Analysis

The study analysed the data to test a second-order structural equation model (SEM) that captures the interrelationships among 11 first-order constructs and three second-order factors: TPACK (loading on TK, TPK, TCK, TPACK), Attitude (PU, PEoU), and Educational Ecosystem Influences (PD, CF, EC, STL, PCI). All SEM analyses were conducted using AMOS (Version 28) with maximum likelihood estimation. Following data screening (range checks, missing data inspection, and outlier review), descriptive statistics were computed for all variables.

Because the TPR scale had been psychometrically validated elsewhere (Li et al., 2024), the corresponding measurement model was specified, and the second-order structural model was then estimated to evaluate direct and indirect paths among the higher-order factors. Models were estimated using maximum likelihood procedures appropriate for 5-point Likert indicators (Kline, 2023). Model adequacy was judged with a conventional fit index portfolio, x^2/df, RMSEA (with 90% CI), SRMR, CFI, TLI, GFI, and AGFI, against widely cited cut-offs (Hair et al., 2018; Hu & Bentler, 1999). Indirect effects were assessed within the SEM framework to quantify mediation from EEI to Attitude via TPACK, alongside the corresponding total effects (Byrne, 2016). This analytic strategy aligns with the study's aim to quantify the hierarchical structure of technological pedagogical readiness and to partition direct and mediated influences among EEI, TPACK, and Attitude in primary mathematics education.

Common method variance was assessed using Harman's single-factor test. An unrotated exploratory factor analysis including all measurement items revealed that the first factor accounted for 27.01% of the total variance, which is below the recommended threshold of 40%, indicating that common method bias is unlikely to pose a serious concern in this study (Podsakoff et al., 2003).

Second-order construct relationships and hypotheses development

Grounded in TAM, attitudes toward technology arise from perceptions of usefulness and ease that are, in turn, shaped by teachers' knowledge and by contextual supports/constraints (Khong et al., 2023; Mailizar et al., 2021). Prior work shows that TPACK competence tends to precede and bolster positive attitudes (e.g., higher TPACK → higher PU/PEoU/intentions) (Khong et al., 2023; Mailizar et al., 2021), while contextual conditions, PD, leadership/resources, collaboration, parental/community support, and students' technology literacy, shape both knowledge and attitudes (Li et al., 2025; Vongkulluksn et al., 2018). Accordingly, EEI → M-TPACK, EEI → Attitude, and M-TPACK → Attitude are specified as the theory-of-change paths most relevant for intervention design, while acknowledging that the reverse path (Attitude → TPACK) is plausible and addressed in the limitations.

Mapping first-order variables to second-order constructs

In the proposed second-order SEM model (see **Figure 1**), the constructs are categorised based on their thematic coherence:

1. Mathematics teachers' TPACK (M-TPACK): This second-order latent variable is reflected by TK, TPK, TCK, and TPACK and does not constitute a novel construct; rather, it contextualizes TPACK to mathematics. These first-order variables together

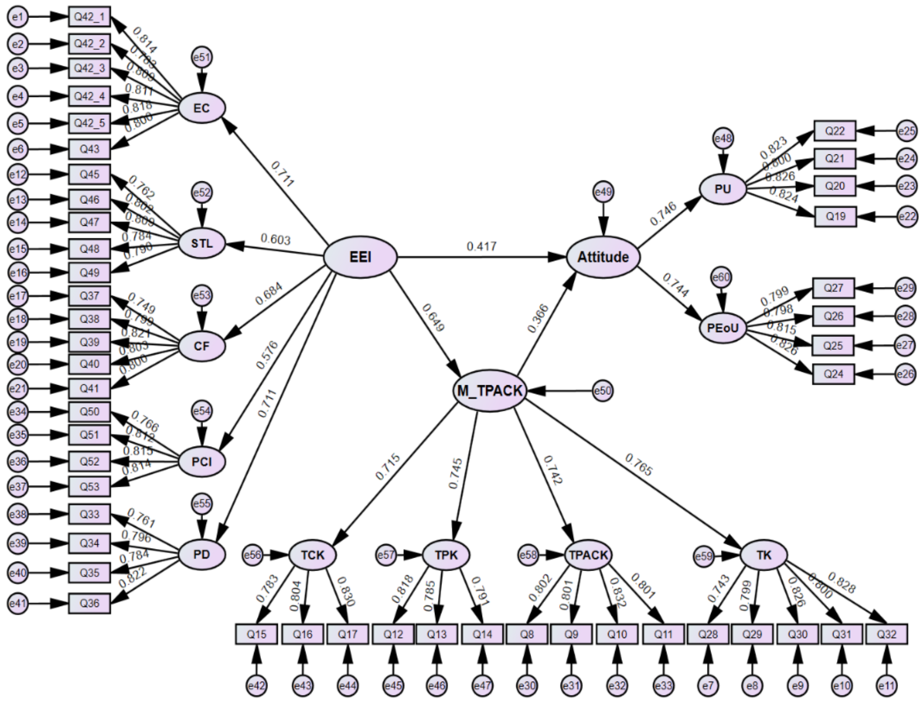

Figure 2. Second-order SEM factor loading and path diagram (Source: Authors' own elaboration)

capture primary mathematics teachers' technological integration competencies across pedagogy and content delivery (Li et al., 2025; Mishra & Koehler, 2006).

2. Attitude: This second-order latent variable encompasses PEoU and PU, reflecting educators' attitudes towards technology. PEoU assesses how educators perceive user-friendly technology, while PU evaluates the perceived benefits of technology in enhancing educational outcomes, particularly in mathematics instruction (Davis et al., 1989; Teo et al., 2017).
3. Educational Ecosystem Influences (EEI): This second-order construct includes PD, EC, CF, PCI, and STL. These variables provide insights into the broader educational environment, from professional growth opportunities and institutional support to the influence of students' and parents' engagement with technology (Li et al., 2025; Porras-Hernández & Salinas-Amescua, 2013).

Hypothesis

Hypothesis 1 (H1)

EEI → Attitude (positive): EEI positively impacts mathematics teachers' attitudes towards technology integration. This hypothesis posits that the educational ecosystem, encompassing professional PD, CF, EC, STL, and PCI, significantly impacts educators' attitudes toward technology integration. A supportive and resource-rich ecosystem is expected to foster positive attitudes towards using technology in mathematics education.

Hypothesis 2 (H2)

EEI → M-TPACK (positive): EEI positively impacts the M-TPACK of mathematics teachers. It is hypothesised that the educational ecosystem not only shapes attitudes but also directly influences the multidimensional construct of M-TPACK, representing the educators' knowledge and capability to effectively integrate technology into their teaching practices.

Hypothesis 3 (H3)

M-TPACK → Attitude (positive): M-TPACK positively influences mathematics teachers' attitudes towards technology integration. This hypothesis suggests a direct relationship between educators' technology integration competencies (M-TPACK) and their attitudes towards technology usage in education.

By delineating these relationships, the study aims to unravel the intricate dynamics within the educational ecosystem that facilitate or hinder technology integration, providing a nuanced understanding of the factors that drive educators' technological adoption in mathematics education.

FINDINGS

Second-Order Construct Validation

In **Figure 2**, the factor loadings from the Second-order SEM, showing the relationships between the observed variables (survey items), first-order variables (constructs), and second-order variables, are recorded.

Table 2. Model fit values

Fit indices	Good fit values	Acceptable fit values	The model fit values	Assessment
X^2/df	$0 < x^2/df < 3$	$3 \leq x^2/df < 5$	1.187	Good
RMSEA	0 < RMSEA < 0.05	0.05 ≤ RMSEA < 0.10	0.018	Good
SRMR	0 < SRMR < 0.05	0.05 ≤ SRMR < 0.08	0.043	Good
GFI	0.95 ≤ GFI ≤ 1	0.90 ≤ GFI < 0.95	0.915	Acceptable
AGFI	0.90 ≤ AGFI ≤ 1	0.85 ≤ AGFI < 0.90	0.906	Good
NFI	0.95 ≤ NFI ≤ 1	0.90 ≤ NFI < 0.95	0.927	Acceptable
CFI	0.95 ≤ CFI ≤ 1	0.90 ≤ CFI < 0.95	0.988	Good
TLI	0.95 ≤ TLI ≤ 1	0.90 ≤ TLI < 0.95	0.987	Good

Note. x^2/df = chi-square divided by degrees of freedom; RMSEA = root mean square error of approximation; SRMR = standardized root mean square residual; GFI = goodness-of-fit index; AGFI = adjusted goodness-of-fit index; NFI = normed fit index; CFI = comparative fit index; TLI = Tucker–Lewis index. Lower is better for RMSEA/SRMR; higher (closer to 1) is better for GFI/AGFI/NFI/CFI/TLI. Cutoffs reflect commonly cited guidelines (e.g., Hair et al., 2018; Byrne, 2016; Kline, 2023); they are heuristics rather than strict pass/fail rules

Individual items to first-order variables

The factor loadings presented in **Figure 2** affirm a solid measurement model, reflecting the strength of the connections within the structural equation framework. EC, gauged by items Q42_1 to Q43, demonstrate high loadings (0.783 to 0.818, $p < 0.001$), indicating a reliable measure of the diverse challenges educators face. TK, as represented by items Q28 to Q32, shows strong factor loadings (0.743 to 0.828, $p < 0.001$), which effectively capture the teachers' perceptions of technology's educational role. STL is aptly measured by items Q45 to Q49, with loadings ranging from 0.762 to 0.809 ($p < 0.001$), reflecting teachers' assessments of their students' technology proficiency. Items Q37 to Q41 assess CF and exhibit substantial loadings (0.749 to 0.821, $p < 0.001$), pointing to the significance of school resources and support systems. PU and PEoU, measured by items Q19 to Q27, are confirmed as reliable indicators with high loadings (0.798 to 0.826, $p < 0.001$). TCK and TPK are supported by items Q15 to Q17 and Q12 to Q14, respectively, with robust loadings (0.783 to 0.83 for TCK and 0.785 to 0.818 for TPK, $p<0.001$). The loadings for PCI items Q50 to Q53 (0.766 to 0.815, $p < 0.001$) and PD items Q33 to Q36 (0.761 to 0.822, $p < 0.001$) validate these constructs as accurately reflecting the survey's domains. In sum, these specific factor loading ranges verify the effectiveness of the survey items in capturing the constructs, ensuring a dependable basis for exploring the intricacies of technology integration within mathematics education.

From First-Order to Second-Order Variables

The SEM results, recorded in **Figure 2**, articulate a distinct hierarchy within the measured constructs, delineating how various aspects of the educational environment and teacher knowledge are aggregated into broader categories. EEI is predominantly defined by factors such as EC and PD, both showing strong loadings of 0.711 ($p < 0.001$), which underscores the profound impact of these aspects on the educational environment. Other components of EEI, like STL and CF, also contribute significantly, with loadings of 0.603 (p < 0.001) and 0.684 (p < 0.001), respectively, while PCI demonstrates a moderate but essential contribution with loading of 0.576 ($p < 0.001$). In the realm of teacher expertise, the M-TPACK construct incorporates substantial contributions from TCK at 0.715 ($p < 0.001$), TPK at 0.745 ($p < 0.001$), and an overarching TPACK component at 0.742 ($p < 0.001$), signalling the essential role of these knowledge domains in mathematics teachers' comprehensive technological competence. The highest loading is seen with TK at 0.765 ($p < 0.001$), suggesting that teachers' fundamental beliefs and understanding of technology play a critical role in the broader construct of M-TPACK. Attitudes towards technology are primarily influenced by the PEoU and PU, with respective loadings of 0.744 ($p < 0.001$) and 0.746 ($p < 0.001$), illustrating that the practicality and perceived benefits of technology are central to shaping mathematics teachers' attitudes towards its integration in the classroom. These findings paint a detailed picture of the interconnectedness of individual and environmental factors and their collective influence on educators' readiness to embrace technology within mathematics education.

The strong standardized loadings from items to first-order factors and from first-order to second-order factors provide robust support for the hypothesized second-order measurement model. Together with the reported global fit indices, these loadings indicate a coherent latent structure consistent with our operationalization of TPACK, TAM (PU, PEoU), and educational ecosystem dimensions in primary mathematics education. The pattern and magnitude of loadings show that each first-order construct contributes meaningfully to its parent second-order factor, with differences in loading size reflecting indicator salience rather than causal influence. These measurement results justify proceeding to the structural analysis of how EEI and M-TPACK relate to teachers' attitudes toward technology integration.

Model Evaluation

The SEM model's fit was assessed using several indices, each with established thresholds for good and acceptable fits (see **Table 2**). The chi-square to degrees of freedom ratio (x^2/df) is 1.187, which is well within the range for a good fit, indicating that the model does not significantly differ from the observed data. The RMSEA is 0.018, falling below the 0.05 threshold for a good fit, which suggests a close fit of the model with the data. The SRMR at 0.043 also meets the criteria for a good fit, further confirming the model's suitability. Also, the GFI and the AGFI are 0.915 and 0.906, respectively, which are slightly below the threshold for a good fit but are well within acceptable limits, suggesting an adequate fit of the model to the observed data. The NFI was 0.927, indicating an acceptable level of incremental fit. Lastly, the CFI and the TLI exceed the 0.95 threshold for a good fit, with values of 0.988 and 0.987, respectively. These high values suggest that the model provides a highly accurate representation of the data and confirm the model's robustness. Therefore, it can be concluded that the second-order SEM model demonstrates an overall good fit with the data according to the fit values provided, indicating that the proposed scale and model structure are appropriate for capturing the complexities of the constructs being measured.

Table 3. Direct, indirect, and total effect

	Direct effect		Indirect effect		Total effect		Results
	β	p	β	p	β	p	
H1. EEI → Attitude	0.417	< 0.001	0.237	< 0.001	0.655	< 0.001	Accepted
H2. EEI → M-TPACK	0.649	< 0.001			0.649	< 0.001	Accepted
H3. M-TPACK → Attitude	0.366	< 0.001			0.366	< 0.001	Accepted

Note: β = standardized path coefficient. "Direct" = coefficient on the specified path; "Indirect" = effect via mediator. For H1, the indirect path is EEI → M-TPACK → Attitude (0.649 × 0.366 = 0.237). Total = direct + indirect; H1 shows partial mediation

Path Coefficient Analysis

In examining the relationships proposed in the research model, **Table 3** presents the direct, indirect, and total effects on the paths linking the constructs within the SEM.

The path coefficient analysis yields conclusive support for the first hypothesis (H1), where EEI are hypothesised to positively affect teachers' attitudes toward technology integration. The direct impact of EEI on Attitude manifests a significant path coefficient (β) of 0.417 ($p < 0.001$). In addition, the indirect effect through the mediating influence of M-TPACK is also statistically significant, with a coefficient of 0.237 ($p < 0.001$), resulting in a notable total effect on Attitude of 0.655 ($p < 0.001$). Therefore, H1 is accepted, indicating that the broader educational ecosystem not only directly impacts teachers' attitudes but also indirectly influences attitudes through its effect on M-TPACK. For the second hypothesis (H2), which considers the direct impact of EEI on M-TPACK, the analysis shows a significant path coefficient of 0.649 ($p < 0.001$). This substantial effect affirms the hypothesis, accepting that EEI directly contributes to enhancing teachers' M-TPACK, encompassing their knowledge and application of technology in pedagogical practices. Moreover, the third hypothesis (H3) addresses the influence of M-TPACK on Attitude. The data analysis indicates a positive direct relationship, with a path coefficient of 0.366 ($p < 0.001$). This significant coefficient supports the acceptance of H3, confirming that M-TPACK plays a significant role in shaping teachers' attitudes towards integrating technology in the classroom.

The path coefficient analysis corroborates the model's structural relations, showing that the educational ecosystem (EEI) and teachers' technological–pedagogical competence (M-TPACK) jointly shape attitudes toward technology in primary mathematics. EEI exerted a direct effect on Attitude ($\beta = 0.417$, $p < .001$) and an additional indirect effect via M-TPACK ($\beta = 0.237$, $p < .001$), yielding a sizable total effect ($\beta = 0.655$, $p < .001$). EEI also strongly predicted M-TPACK ($\beta = 0.649$, $p < .001$), and M-TPACK, in turn, positively predicted Attitude ($\beta = 0.366$, $p < .001$), indicating partial mediation of the EEI → Attitude link. Collectively, these results highlight that supportive professional development and institutional context (EEI) foster teachers' technology-integration attitudes both directly and by strengthening their integrated technological, pedagogical, and content knowledge (M-TPACK), offering a comprehensive account of how environmental and knowledge factors co-produce readiness for educational technology adoption.

DISCUSSION

Integrated Impact of EEI on Mathematics Teachers' TPACK in Primary Education

The EEI provides a comprehensive perspective on the external factors that shape primary mathematics teachers' capabilities to integrate technology within their pedagogical practices, as reflected in their M-TPACK. Understanding how the components of EEI synergistically interact to create a supportive environment for technology integration is crucial (Li et al., 2025; Voogt et al., 2013). PD (Thurm et al., 2024), EC, CF (Rehman et al., 2025), PCI, and STL (Soriano-Alcantara et al., 2024) collectively influence the educational setting, with each element playing a critical role in fostering or hindering technology integration (Tondeur et al., 2017). Consistent with this view, the structural equation model shows that EEI is a strong predictor of M-TPACK ($\beta = 0.649$, $p < .001$), with EC and PD loading most strongly on EEI (both 0.711, $p < .001$), followed by CF (0.684), STL (0.603), and PCI (0.576). This pattern identifies curriculum/testing pressures and professional learning as the most influential levers within the ecosystem, supported by leadership/resources, students' technology literacy, and family/community support. Professional development (PD) becomes significantly more impactful when it is aligned with an understanding of the existing educational challenges (EC), creating more targeted and relevant training programs (Ertmer et al., 2012; Thurm et al., 2024). When policymakers and educational leaders tailor professional development programs to directly address these challenges, they equip teachers with the necessary skills and confidence. For instance, if a school recognises the challenge posed by standardised testing in mathematics and the need for enhanced technology integration to improve student outcomes, a tailored professional development program can equip teachers with the strategies and tools to effectively integrate technology, thereby addressing the specific challenge and fostering more effective teaching practices.

Similarly, the impact of PD is magnified in contexts where contextual factors (CF) are favourable, suggesting that the infrastructure and school culture significantly amplify or mitigate the benefits of professional training (Ertmer & Ottenbreit-Leftwich, 2010). The loadings for contextual factors (CF = 0.684, $p < .001$) corroborate this enabling role of resources, leadership, and collaborative culture. Moreover, the study found that the dynamics between PCI and STL with teachers' M-TPACK underscore a reciprocal relationship where not only do teachers influence their students' technological literacy, but students' adeptness in technology can also catalyse teachers' motivation to enhance their M-TPACK (Kim et al., 2013). While the cross-sectional model does not test bidirectionality, the positive contributions of students' technology literacy (STL = 0.603, $p < .001$) and parental and community involvement (PCI = 0.576, $p < .001$) to EEI suggest that learner readiness and community engagement are meaningful contextual supports for strengthening teachers' integrated knowledge. This symbiosis between student proficiency and teacher development in technology skills highlights the need for a responsive educational ecosystem that adapts to the evolving technological competencies of its learners. The collective influence of EEI on M-TPACK suggests that an integrative approach is necessary for understanding and improving technology integration in education. Teachers' M-TPACK development is most effective in a holistic ecosystem that balances professional development with supportive contextual factors, acknowledges and addresses education challenges, and leverages the synergistic potential of parental and community involvement and students' technology literacy. This integrated perspective underscores the complexity of technology integration in primary mathematics education, suggesting that initiatives aimed at enhancing mathematics teachers' TPACK should consider the diverse nature of EEI to optimise educational outcomes in the technology-rich post-pandemic era (Mishra et al., 2023; Polly, 2024; Yildiz & Arpaci, 2024).

Shaping Teachers' Attitudes Toward Technology Integration: The Role of EEI in Primary Mathematics

The influence of the EEI extends beyond the development of mathematics teachers' TPACK to significantly shape their attitudes towards technology in primary mathematics education (Gurer, 2021; Li, 2023). In the model, EEI exerts a significant direct effect on Attitude ($\beta = 0.417$, $p < .001$) and an additional indirect effect via M-TPACK ($\beta = 0.237$, $p < .001$), yielding a substantial total effect ($\beta = 0.655$, $p < .001$). One significant finding is that the EEI, characterised by professional development, parental and community involvement, and the availability of resources, creates a milieu that can foster or impede the adoption of technological tools in teaching practices. Within EEI, professional development and educational challenges loaded most strongly (both 0.711), followed by contextual factors (CF = 0.684), students' technology literacy (STL = 0.603), and parental and community involvement (PCI = 0.576), indicating which levers are most consequential for shaping attitudes.

A supportive EEI, enriched with continuous and relevant professional development, empowers primary mathematics teachers by equipping them with up-to-date knowledge and skills in technology integration, thereby positively influencing their attitudes towards its use (Tondeur et al., 2017). When professional development explicitly addresses assessment pressures and curriculum demands (EC)—for example, modelling how dynamic geometry or data tools can support standards-aligned tasks—teachers' perceived usefulness and ease of use tend to improve, translating into more favourable attitudes (Rehman et al., 2025; Thurm et al., 2024). Importantly, the indirect effect is smaller than the corresponding direct effect of EEI on Attitude ($\beta = 0.417$), indicating a pattern of partial mediation rather than full mediation. This suggests that while M-TPACK constitutes an important mechanism through which ecosystem conditions shape teachers' attitudes, contextual influences also exert a substantial direct impact that is not fully transmitted through teachers' knowledge alone. From a practical perspective, this partial mediation implies that initiatives focused solely on enhancing M-TPACK may be insufficient to foster sustained positive attitudes unless they are accompanied by supportive institutional conditions, such as aligned professional development, leadership endorsement, and reduced contextual constraints.

Furthermore, when educators perceive that technology is valued and supported within their community and by parents, their confidence and motivation to incorporate technology into their pedagogy are enhanced (Vongkulluksn et al., 2018). Simultaneously, we found that resource availability also plays a pivotal role in shaping primary mathematics teachers' attitudes. The accessibility of technological tools and infrastructure within the school setting can significantly lower the barriers to technology integration, making teachers more inclined to explore and adopt new technologies in their teaching (Ertmer et al., 2012; Polly, 2024), consistent with the sizable contextual factors' (CF) loading in the measurement model. Conversely, a lack of resources can foster a sense of frustration and scepticism towards the feasibility of technology integration, negatively impacting teachers' attitudes.

One important finding is that the interplay between EEI and teachers' attitudes is also reflected in their perceptions of students' technology literacy. When teachers recognise their students' proficiency and comfort with technology, they are more likely to adopt pedagogical strategies incorporating technology, believing that such approaches will resonate with their learners and enhance educational outcomes (Kim et al., 2013), a pattern aligned with the students' technology literacy contribution to EEI (0.603). Taken together, these results suggest that attitudes are not merely individual dispositions; they are conditioned by ecosystem features that policy and leadership can shape. Prioritising challenge-aligned professional development and supportive organisational conditions, while leveraging student readiness and community engagement, offers a practical route to improving teachers' openness to technology integration in primary mathematics. Therefore, it can be said that the EEI significantly impacts teachers' attitudes towards technology in education, with professional development, educational challenges, parental and community support, resource availability, and perceptions of students' technological proficiency all playing crucial roles. By fostering a positive educational ecosystem, stakeholders can facilitate more favourable attitudes towards technology integration among primary mathematics teachers, ultimately leading to enhanced educational practices that leverage technological advancements.

The Interplay of EEI, M-TPACK, and Teachers' Attitudes in Technology Integration

The intricate relationship between M-TPACK and teachers' attitudes towards technology integration is a cornerstone of effective educational practices. Educators who possess a robust M-TPACK are more inclined to hold positive attitudes towards the use of technology in their teaching, a sentiment echoed in the literature which suggests that a deep understanding and competence in integrating technology, pedagogy, and content knowledge foster a conducive attitude towards technology adoption in educational settings (Joo et al., 2018; Yang et al., 2019). Consistent with this literature, the second-order structural equation model showed that EEI had a significant direct association with Attitude ($\beta = 0.417$, $p < .001$) and a strong association with M-TPACK ($\beta = 0.649$, $p < .001$), while M-TPACK in turn related positively to Attitude ($\beta = 0.366$, $p < .001$). Moreover, EEI also displayed an indirect association with Attitude via M-TPACK ($\beta = 0.237$, $p < .001$), reinforcing the idea that supportive ecosystems, through professional development, leadership, and collaborative cultures, work through teachers' knowledge as well as directly on their beliefs (Ertmer & Ottenbreit-Leftwich, 2010; Khong et al., 2023; Thurm et al., 2024). In practical terms, schools that align

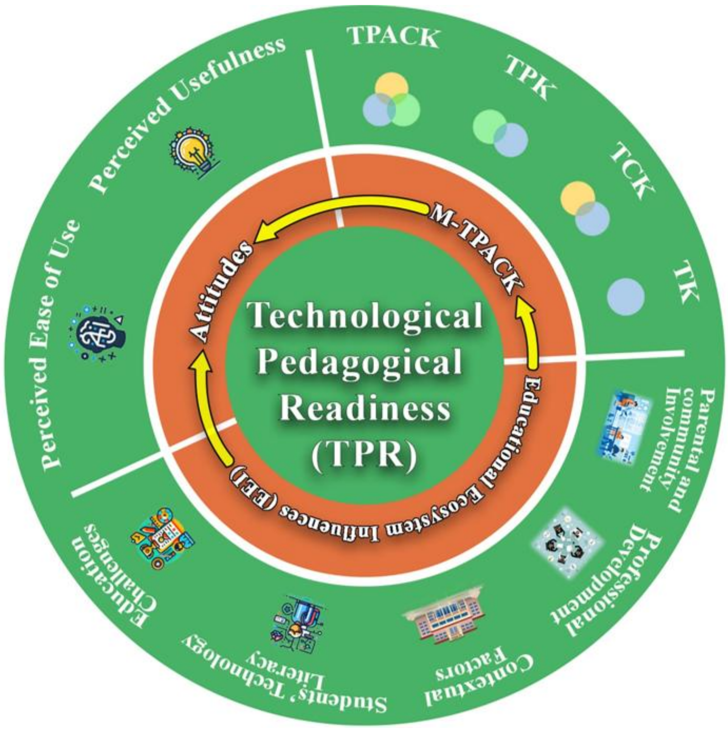

Figure 3. Second-order TPR structural model (Source: Authors' own elaboration)

PD with curricular demands and provide time, tools, and collegial support tend to build teachers' M-TPACK, which in turn strengthens perceptions of usefulness and ease of use, sharpening attitudes in favour of integration.

Therefore, the results delineate a coherent triad consistent with **Figure 3**: EEI exerts a substantial direct effect on teachers' attitudes and an additional indirect effect via M-TPACK, and EEI also strengthens teachers' M-TPACK. In the tested model, the causal flow runs from EEI to M-TPACK and Attitude, and from M-TPACK to Attitude; no reverse paths were estimated. Accordingly, efforts to advance technology integration should act on all three fronts, enriching the EEI (e.g., professional development, leadership and resourcing, parent–community support, students' technology literacy), deepening mathematics teachers' TPACK, and cultivating positive attitudes, rather than targeting any single component in isolation.

Implications

Integrating technology in primary mathematics education requires a comprehensive understanding of the dynamic interplay between the educational ecosystem influences, teachers' M-TPACK, and their attitudes towards technology in the post-pandemic, increasingly AI-mediated classroom (Bueno & Niess, 2023; Li, 2023; Li et al., 2025). This interconnectedness forms the foundation for developing strategies that foster an environment conducive to effective technology integration. Building on this study's empirical results, the Technological Pedagogical Readiness (TPR) framework (see **Figure 3**) was empirically validated in the context of primary mathematics education. This framework delineates the hierarchical relationships among EEI, M-TPACK, and teachers' attitudes toward technology integration in primary mathematics education, including a direct EEI→Attitude pathway and an indirect EEI→M-TPACK→Attitude pathway depicted in the model. By clearly specifying these interrelations, the framework synthesizes TPACK/TAM with contextual levers and functions as a diagnostic and design tool for practical implementation and future research in educational technology, guiding the alignment of PD, leadership support, and resource provision with attitudinal drivers (perceived usefulness/ease of use) to strengthen teachers' technological pedagogical readiness.

The TPR structural model emphasizes the need for a comprehensive approach to professional development and technology integration strategies. Educators and school leaders can use the model to audit EEI components (PD, EC, CF, PCI, STL), identify bottlenecks, and prioritise interventions within their institutions. By understanding the interconnectedness of EEI components and their impact on M-TPACK and attitudes, leaders can design needs-based PD explicitly mapped to identified challenges (e.g., pressure from standardised testing), provide protected time and coaching for classroom enactment, strengthen professional learning communities for peer modelling, and align infrastructure plans with intended pedagogical use. Where students' technology literacy is high, leaders can strategically leverage it, for example, by creating student digital leadership or classroom tech-helper roles, to support mathematics teachers' TPACK development and normalise technology-rich mathematics tasks.

The visual representation of the interconnectedness between EEI, M-TPACK, and teacher attitudes offers policymakers a clear understanding of where to direct resources and support. Policies can be developed to strengthen the EEI components, knowing their potential impact on enhancing teachers' technology integration skills and attitudes. Concretely, this implies sustained funding that couples hardware with pedagogy-focused PD, leadership standards that require school-level technology visions, assessment policies that reduce counterproductive EC (e.g., narrow test preparation), and equity-oriented grants targeting under-resourced schools' CF. Embedding monitoring with TPR-aligned indicators (e.g., M-TPACK growth, attitude shifts) will help track policy impact and course-correct.

The TPR structural model provides a structured perspective that can inform future research endeavours. Researchers can use the model to explore specific relationships within and between the constructs, enabling a deeper understanding of how various factors contribute to the successful integration of technology in mathematics education. Priority directions include longitudinal designs to test causal ordering (EEI → M-TPACK → Attitudes), multi-group SEM for measurement and structural invariance (e.g., grade bands, school Socioeconomic Status), and intervention trials that manipulate PD/CF levers and track downstream changes. Extensions that differentiate AI-specific teacher knowledge and attitudes will clarify where the current TPR needs refinement for emerging tools.

Practitioners can use the model as a diagnostic tool to assess and improve their readiness for technology integration in schools or educational systems. A practical cycle is:

(1) Diagnose EEI and M-TPACK with the TPR instrument;

(2) Prioritise two or three leverage points (e.g., PD alignment to EC, leadership signalling, family partnerships);

(3) Implement targeted actions (lesson study with technology, coaching, resource re-allocation);

(4) Monitor change with brief attitude and M-TPACK check-ins; and

(5) Iterate.

By identifying strengths and weaknesses within the EEI and their effects on M-TPACK and attitudes, educators can tailor interventions to target specific areas, thereby fostering a more effective and sustainable integration of technology in teaching and learning processes.

Limitations and Future Research

Limitations

The study's findings are based on a sample of primary mathematics teachers from a specific geographic region. While this provides depth, it may limit the generalizability of the findings to other educational contexts or subject areas (Cohen et al., 2018). Future research could expand to include diverse educational settings and subjects to ascertain the broader applicability of the TPR framework. Moreover, the study's cross-sectional nature provides a snapshot of the relationships between EEI, M-TPACK, and teacher attitudes. However, it does not capture the dynamic nature of these relationships over time. Longitudinal studies could offer more nuanced insights into how these relationships evolve with ongoing changes in educational technology and policy landscapes. Accordingly, the specified directionality (EEI → M-TPACK; EEI → Attitude; M-TPACK → Attitude) should be interpreted cautiously; reverse or reciprocal pathways (e.g., Attitude → M-TPACK) are theoretically plausible and warrant testing with longitudinal, cross-lagged, or experimental designs. Finally, relying on self-reported measures may introduce bias, as teachers' perceptions of their technological readiness and attitudes might not fully capture their actual practices (Bryman, 2016). Future research could incorporate observational or performance-based measures to provide a more comprehensive understanding of primary mathematics teachers' technology integration practices.

Future research directions

Future research could employ longitudinal designs to capture the evolution of technological pedagogical readiness over time. This approach would allow for examining how changes in the educational ecosystem influence teachers' M-TPACK development and attitudes toward technology integration. Also, implementing and evaluating targeted interventions can provide causal insights into how specific elements of EEI influence M-TPACK and attitudes. Future studies could design and assess the impact of tailored professional development programs or technology resource allocations on teachers' technological readiness. To enrich the understanding of the underlying mechanisms and teacher experiences, future research could integrate qualitative methods such as interviews or focus groups. This approach would provide depth to the quantitative findings and offer a holistic view of the factors influencing technology integration in education. Finally, investigating the TPR framework across different educational systems, cultures, or subject disciplines could offer comparative insights. Such studies could illuminate context-specific factors influencing technology integration and provide a more global perspective on technological pedagogical readiness.

CONCLUSION

This study's exploration into the interplay between EEI, M-TPACK, and teachers' attitudes towards technology integration offers significant contributions to educational technology, particularly within primary mathematics education. Drawing on data from 554 primary mathematics teachers in Chongqing, China, and validating the TPR framework via a second-order SEM, the study clarified how contextual conditions shape teachers' technological readiness and dispositions. The findings underscore the critical role of EEI in shaping the M-TPACK of teachers and their attitudes towards technology use. Specifically, EEI strongly predicted M-TPACK, exerted a direct effect on attitudes, and an additional indirect effect via M-TPACK, while M-TPACK itself positively influenced attitudes. Professional development, contextual factors, and the broader educational environment enable teachers to harness technology effectively, enhancing teaching and learning outcomes. These results indicate that primary teachers' readiness is not merely a function of individual knowledge or attitudes but is rooted in the ecosystem within which they work. The demonstrated M-TPACK–attitude pathway suggests that building teachers' integrated technological, pedagogical, and content knowledge is a viable lever for cultivating positive technology dispositions. Accordingly, holistic strategies that align school- and system-level supports with targeted capacity building are warranted. The validated TPR model offers practical lens for diagnosing contextual levers, prioritising professional learning, and guiding policy to accelerate effective technology integration in primary mathematics.

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