

A Conceptual Framework for AI-Enhanced Pedagogical Competence in Secondary Mathematics Education

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Abstract

The rapid development of artificial intelligence (AI) is reshaping secondary mathematics education, challenging conventional expectations of pedagogical competence. This conceptual study presents a framework that redefines teacher expertise by integrating foundational domains Pedagogical Knowledge (PK), Content Knowledge (CK), and Technological Knowledge (TK) with transversal competencies including data literacy, ethical awareness, reflective adaptability, and collaborative engagement. The study examines research on AI in education, mathematics pedagogy, and teacher professional development, emphasising the shortcomings of current models like TPACK in meeting AI-specific requirements, including real-time analytics, algorithmic bias, and intelligent system mediation. The framework was developed using a conceptual methodology through a three-stage process: reviewing foundational literature, synthesising insights on AI applications in classrooms, and aligning competencies with international policy recommendations. The model presents AI as a pedagogical partner that supports adaptive instruction, enhances conceptual understanding, and facilitates ethical, data-informed decision-making, rather than as a replacement for teacher agency. This framework provides essential guidance for educators, policymakers, and researchers to ensure that AI integration in mathematics education is pedagogically sound, ethically grounded, and professionally empowering.

Keywords: AI-enhanced Pedagogy, Transversal competencies, Mathematics education, Teacher competencies

Abstrak

Perkembangan pesat kecerdasan buatan (AI) sedang membentuk semula pendidikan matematik menengah, mencabar jangkauan konvensional terhadap kecekapan pedagogi. Kajian konseptual ini membentangkan rangka kerja yang mentakrifkan semula kepakaran guru dengan mengintegrasikan domain asas Pengetahuan Pedagogi (PK), Pengetahuan Kandungan (CK), dan Pengetahuan Teknologi (TK) dengan kecekapan transversal termasuk literasi data, kesedaran etika, kebolehsuaian reflektif, dan penglibatan kolaboratif. Kajian ini mengkaji penyelidikan mengenai AI dalam pendidikan, pedagogi matematik, dan pembangunan profesional guru, menekankan kekurangan model semasa seperti TPACK dalam memenuhi keperluan khusus AI, termasuk analitik masa nyata, bias algoritma, dan pengantaraan sistem pintar. Rangka kerja ini dibangunkan menggunakan metodologi konseptual melalui proses tiga peringkat: mengkaji literatur asas, mensintesis pandangan tentang aplikasi AI di bilik darjah, dan menyelaraskan kecekapan dengan cadangan dasar antarabangsa. Model ini membentangkan AI sebagai rakan kongsi pedagogi yang menyokong pengajaran adaptif, meningkatkan pemahaman konseptual, dan memudahkan pembuatan keputusan yang beretika dan berasaskan data, dan bukannya sebagai pengganti agensi guru. Rangka kerja ini menyediakan panduan penting untuk pendidik, pembuat dasar dan penyelidik bagi memastikan integrasi AI dalam pendidikan matematik kukuh dari segi pedagogi, beretika dan memperkasakan secara profesional.

Kata kunci: Pedagogi yang dipertingkatkan AI, Kecekapan transversal, Pendidikan Matematik, Kecekapan guru

INTRODUCTION

The ability to create, carry out, and assess successful teaching strategies that foster conceptual mastery, procedural fluency, and critical thinking has traditionally been defined as pedagogical competence in mathematics. The teaching and learning of mathematics in particular are changing because of the quick development of artificial intelligence (AI). Teachers' pedagogical roles are being redefined, and instructional practices are being increasingly shaped by chatbots, adaptive platforms, intelligent tutoring systems, and data-driven analytics. AI tools have shown promise in supporting differentiated instruction, personalising learning pathways, and scaffolding conceptual understanding in secondary mathematics education, where students frequently struggle with abstract concepts and problem-solving techniques (Holmes et al., 2022; Luckin, 2023). The need for teachers to acquire improved pedagogical competence that goes beyond conventional teaching methods is highlighted by this increasing digital shift.

The integration of AI necessitates that educators exhibit technological proficiency, ethical consciousness, and the capacity to make data-driven instructional choices (Chen et al., 2021; Zawacki-Richter et al., 2019). Teachers now have to interpret real-time analytics, mediate student-intelligent system interactions, and strike a balance between machine-assisted support and human-centered pedagogy. Without appropriate theoretical guidance and professional preparation, the integration of AI risks exacerbating inequities, creating ethical quandaries, and reducing teacher agency (Williamson & Eynon, 2020).

Although frameworks such as the Technological Pedagogical Content Knowledge (TPACK) model have significantly advanced understanding of how teachers integrate digital tools, they remain insufficient for addressing the complex demands of AI-mediated mathematics teaching. TPACK describes the intersections among pedagogical, content, and technological knowledge, yet it does not account for teachers' responsibilities in interpreting real-time analytics, identifying algorithmic bias, or mediating student-AI interactions—all of which increasingly shape instructional processes in secondary mathematics (Koehler et al., 2014; Williamson & Eynon, 2020). Emerging extensions such as AI-TPACK and intelligent-TPACK (iTPACK) highlight the need for AI-related knowledge, but these models primarily emphasise technological familiarity rather than the competence-based mechanisms teachers require to make adaptive, ethical, and data-informed decisions during instruction (Ning, 2024; Ren, 2025). As recent reviews show, frameworks rooted in static knowledge domains are unable to fully capture how AI-driven feedback loops influence moment-to-moment pedagogical reasoning in mathematics classrooms (Schmid et al., 2024).

Additionally, current models do not theorise *how* teachers should negotiate the pedagogical, ethical, and analytical implications of AI-generated outputs. Research indicates that teachers often struggle to interpret learning analytics, address issues of data privacy, or evaluate the reliability of automated recommendations—competencies increasingly recognised as central to professional practice in AI-supported environments (Hershkovitz et al., 2024; UNESCO, 2023; OECD, 2023). These challenges reveal a substantive theoretical gap: existing frameworks describe what teachers should know, but not how they should act when AI becomes an active participant in instruction. Therefore, a new framework is needed—one that positions AI as a pedagogical partner and integrates transversal competencies such as data literacy, ethical awareness, reflective adaptability, and collaborative engagement. The present study addresses this gap by proposing a framework that synthesises PK, CK, and TK with AI-specific professional competencies to guide teachers' pedagogical decision-making in secondary mathematics education.

LITERATURE REVIEW

Pedagogical Competence in Mathematics Education (PK, CK)

Mathematical pedagogical competence is conventionally defined as the convergence of educators' pedagogical knowledge (PK) and content knowledge (CK). Competent educators must formulate and implement instructional strategies that cultivate procedural fluency, conceptual comprehension, and problem-solving abilities. Recent systematic reviews demonstrate that pedagogical content knowledge (PCK) has a substantial, albeit inconsistent, impact on student achievement, highlighting that competence alone is inadequate without a clear understanding of its application in classroom practice (Fukaya et al., 2025). In secondary mathematics, novice educators frequently encounter difficulties in integrating multiple representations, diagnosing misconceptions, and connecting tasks to overarching learning objectives, underscoring ongoing challenges in converting pedagogical knowledge (PK) and content knowledge (CK) into effective teaching practices (Li et al., 2024). Research into mathematics teacher educators have indicated that, although theoretical frameworks are comprehensive, they frequently lack clarity regarding the process by which teachers convert pedagogical knowledge (PK) and content knowledge (CK) into context-specific instructional decisions (Castro Superfine et al., 2024). Concurrent studies underscore the significance of visualisation in mathematics instruction. Meta-analytical results indicate that dynamic representations markedly improve student comprehension of abstract concepts (Schoenherr et al., 2024). These insights indicate that AI-driven visualisations, simulations, and error-detection tools can enhance teachers' content knowledge and reinforce pedagogical knowledge by facilitating real-time identification of misconceptions and aiding adaptive explanations. Consequently, PK and CK are essential foundations; however, their implementation in AI-mediated classrooms necessitates enhancement through intelligent supports that facilitate content clarity and adaptive instructional decisions.

Intelligent Tutoring Systems and Adaptive Platforms (TK)

In addition to PK and CK, technological knowledge (TK) has emerged as a crucial component of teachers' professional proficiency. Research on intelligent tutoring systems (ITS) and adaptive platforms demonstrates their ability to provide personalised practice and immediate feedback, although results are contingent on context (Son et al., 2024). A systematic review of AI-driven intelligent tutoring systems in K–12 mathematics demonstrated quantifiable enhancements in student performance, while underscoring the essential role of teacher mediation in maintaining learning advancements (Létourneau et al., 2025). Likewise, extensive evidence from the COVID-19 era indicated that AI-enhanced practice platforms facilitated advancements in mathematics performance (Spitzer et al., 2024). These findings indicate that TK should be redefined not merely as operational knowledge of digital tools, but as the ability to coordinate AI-driven feedback, align automation with educational objectives, and integrate intelligent systems within a comprehensive pedagogical framework. TK thus evolves into a dynamic domain wherein educators employ AI not solely for instructional delivery but also for real-time informed decision-making, directly correlating with the outcomes outlined in the proposed framework.

Chatbots and Generative AI

Recent trends in AI implementation in education emphasise chatbots and generative AI technologies. Chatbots are increasingly acknowledged for their capacity to deliver immediate assistance and motivational feedback, consequently alleviating teacher workload. Nonetheless, issues with accuracy and over-reliance persist (Labadze et al., 2023). Generative AI tools, like ChatGPT, have shown promise in mathematics education by aiding problem-solving, providing explanations, and offering

tutoring; however, challenges related to equity, assessment integrity, and the necessity for teacher-designed scaffolding remain (Almarashdi et al., 2024). These findings emphasise that the effective utilisation of generative AI demands educators to integrate technological knowledge with critical professional judgement, ensuring that AI enhances rather than replaces pedagogical expertise. This corresponds with the reflective and adaptive competence dimension of the framework, wherein educators critically assess AI recommendations and progressively enhance their strategies.

Learning Analytics and Data Literacy

Another area of AI integration pertains to learning analytics, which furnish educators with dashboards and data-driven insights regarding student progress. Research indicates that analytics enhance teacher responsiveness through the identification of learning patterns and error trends (Rundquist, 2024; Hershkovitz et al., 2024). Many educators, however, do not possess the necessary skills to interpret analytics or to implement them effectively. This gap underscores the essential requirement for data literacy as a professional competency. In classrooms enriched by AI, data literacy should encompass not only technical interpretation but also ethical awareness and reflective adaptability. Educators should assess the reliability of AI-generated outputs, address algorithmic bias, and modify teaching methods based on empirical evidence, thereby maintaining professional autonomy. This is directly linked to the framework's transversal competencies, which regard data literacy and ethics as essential for the responsible adoption of AI.

Limitations of Existing Competence Models

Although several frameworks attempt to conceptualise teacher knowledge for technology integration, none sufficiently address the unique demands of AI-mediated mathematics instruction. The Technological Pedagogical Content Knowledge (TPACK) framework (Koehler et al., 2014) provides a foundational model but remains primarily descriptive, offering limited guidance for managing real-time analytics, algorithmic bias, or AI-driven feedback loops (Schmid et al., 2024). It does not theorise how teachers should interpret or respond to AI-generated insights or navigate machine-human co-orchestration. Extensions such as AI-TPACK (Ning, 2024) and iTPACK (Ren, 2025) acknowledge the emergence of AI in education but continue to treat AI as a technological tool, focusing on knowledge elements rather than the competence-based mechanisms required to evaluate, adapt, and ethically employ AI recommendations. Similarly, structural models such as SAMR conceptualise technology integration as levels of substitution to redefinition but do not address the pedagogical, ethical, or analytical complexities introduced by AI systems.

International frameworks, including UNESCO's AI Competency Framework (2023) and the OECD Digital Education Outlook (2023), emphasise the importance of data literacy, transparency, and ethical AI use at the system level. However, they do not articulate how these competencies intersect with subject-specific pedagogical reasoning particularly in mathematics, where AI feedback can influence conceptual explanations, task sequencing, and real-time instructional strategy. Collectively, these limitations indicate a theoretical gap: existing models describe what teachers should know, but not how they should act when engaging with AI systems that continuously generate data, surface misconceptions, or propose instructional actions. The present study responds to this gap by proposing an integrated framework that synthesises PK, CK, and TK with transversal competencies of data literacy, ethical judgement, reflective adaptability, and collaborative engagement to guide teachers' professional practice in AI-mediated mathematics classrooms.

Novelty and Theoretical Contribution of the Proposed Framework

Existing competence models such as TPACK (Koehler et al., 2014), AI-TPACK (Ning, 2024), iTPACK (Ren, 2025), and other related frameworks have been instrumental in shaping our understanding of teacher knowledge for technology integration. However, these models provide only partial guidance when applied to the increasingly complex reality of AI-mediated mathematics classrooms. While they articulate the relationships among pedagogical, content, and technological knowledge, they do not adequately theorise the *dynamic, real-time, and ethically sensitive* processes that arise when teachers interact with AI systems during instruction. As secondary mathematics classrooms become more intertwined with analytics dashboards, adaptive systems, chatbots, and automated feedback mechanisms, these limitations become especially pronounced.

A closer examination reveals several important gaps. The TPACK model, although foundational, does not address the interpretive demands of learning analytics, the risks of algorithmic bias, or the evolving teacher–AI interaction patterns that shape modern instructional decision-making. AI-TPACK extends the technological knowledge dimension to incorporate AI tools, but it remains largely tool-centred and does not theorise the mechanisms through which analytics, ethics, or adaptive reasoning influence pedagogy. Similarly, iTPACK emphasises the role of intelligent systems but focuses primarily on knowledge *requirements*, offering limited guidance on the competences teachers need to negotiate AI outputs, respond to automated recommendations, or manage the ethical implications of algorithm-mediated learning. International competency frameworks, such as those developed by UNESCO and the OECD, highlight ethics and data literacy as essential professional skills, yet they do not integrate these competencies with the specific pedagogical reasoning processes required in mathematics teaching. Together, these gaps underscore the need for a more comprehensive theoretical framework that accounts for the distinctive demands of AI-enhanced mathematics pedagogy.

The AI-Enhanced Pedagogical Competence Framework proposed in this study extends existing theoretical models by offering several novel contributions. First, it reconceptualises teacher competence not as a static body of knowledge but as an adaptive orchestration of PK, CK, TK, and transversal competencies in real time. The framework emphasises *how* teachers mobilise these domains dynamically when interacting with AI systems, shifting the focus from knowledge possession to competence enactment. Second, it positions data literacy and ethical reasoning as central pedagogical mechanisms rather than peripheral considerations. In AI-rich environments, teachers must continuously evaluate the credibility of analytics, anticipate potential biases, and make informed instructional adjustments; the framework therefore embeds these dimensions at the core of pedagogical reasoning. Third, the framework introduces a conceptualisation of AI not merely as a technological tool but as a pedagogical partner. This perspective highlights AI's role in shaping instructional responsiveness, guiding conceptual explanations, and influencing decision-making pathways. Instead of depicting teachers as passive users of AI, the framework foregrounds their agency in interpreting, adapting, and moderating AI-generated insights. Finally, the framework offers a mathematics-specific contribution by theorising how AI enhances disciplinary practices such as multiple-representation reasoning, diagnosis of misconceptions, and adaptive sequencing of mathematical tasks. Unlike domain-general models, this framework situates AI integration directly within the epistemic and pedagogical practices of mathematics education.

Collectively, these contributions provide a more comprehensive and practice-oriented theoretical account of what pedagogical competence entails in AI-mediated mathematics classrooms. They also establish the groundwork for future empirical research, positioning the framework as an advancement beyond existing knowledge-based models toward a more dynamic, ethically grounded, and discipline-specific understanding of AI-enhanced teacher competence. TK thus evolves into a dynamic domain wherein educators employ AI not solely for instructional delivery but also for real-time informed decision-making, directly correlating with the outcomes outlined in the proposed framework. In addition to PK and CK, technological knowledge (TK) has emerged as a crucial component of teachers' professional proficiency. Research on intelligent tutoring systems (ITS) and

adaptive platforms demonstrates their ability to provide personalised practice and immediate feedback, although results are contingent on context (Son et al., 2024). A systematic review of AI-driven intelligent tutoring systems in K–12 mathematics demonstrated quantifiable enhancements in student performance, while underscoring the essential role of teacher mediation in maintaining learning advancements (Létourneau et al., 2025). Likewise, extensive evidence from the COVID-19 era indicated that AI-enhanced practice platforms facilitated advancements in mathematics performance (Spitzer et al., 2024). These findings indicate that TK should be redefined not merely as operational knowledge of digital tools, but as the ability to coordinate AI-driven feedback, align automation with educational objectives, and integrate intelligent systems within a comprehensive pedagogical framework. TK thus evolves into a dynamic domain wherein educators employ AI not solely for instructional delivery but also for real-time informed decision-making, directly correlating with the outcomes outlined in the proposed framework.

METHODOLOGY

This study adopted a conceptual research design to develop a theoretical framework that explains how artificial intelligence (AI) enhances pedagogical competence in secondary mathematics education. Conceptual research was selected because it enables the synthesis of diverse theoretical perspectives and the construction of integrative models in areas where technological developments such as AI advance more rapidly than existing educational theory. As Gilson and Goldberg (2015) emphasise, conceptual papers are crucial when scholarly understanding lags behind innovation, a condition that accurately describes the evolving landscape of AI in education. Rather than collecting empirical data, this study aimed to build theoretical clarity by critically analysing existing research, identifying conceptual gaps, and mapping relationships among emergent constructs.

The framework's foundation draws upon established domains of Pedagogical Knowledge (PK), Content Knowledge (CK), and Technological Knowledge (TK), as articulated within the Technological Pedagogical Content Knowledge (TPACK) model (Koehler et al., 2014). However, the review revealed that PK, CK, and TK alone do not adequately capture the dynamic, data-intensive, and ethically complex nature of AI-mediated instruction. This recognition necessitated the incorporation of additional competencies relevant to AI-enhanced pedagogy, including data literacy, ethical awareness, reflective adaptability, and collaborative engagement. To ensure methodological transparency and rigour, the literature included in the analysis was selected according to explicit criteria. Peer-reviewed journal articles, systematic reviews, meta-analyses, and authoritative policy reports (e.g., UNESCO 2023; OECD 2023; U.S. Department of Education 2023) were prioritised. Sources published between 2019 and 2025 were emphasised to reflect current advances in AI technologies. Studies were included if they addressed mathematics education, teacher competence, learning analytics, AI tools (such as intelligent tutoring systems, adaptive platforms, chatbots, and generative AI), or ethical considerations related to AI. Publications lacking conceptual relevance or methodological robustness were excluded. This selection process followed a PRISMA-lite logic, beginning with broad identification of sources, followed by screening for relevance, assessment for conceptual contribution, and final synthesis of eligible literature.

A structured concept-mapping protocol guided the development of the theoretical framework. The process began with extracting key constructs from the selected literature, including PK, CK, TK, and AI-related competencies. These constructs were then grouped into thematic clusters representing foundational teacher knowledge and transversal AI-enhanced competencies. Relational mapping was subsequently conducted to examine how these constructs interact in AI-mediated teaching—for example, how real-time analytics influence instructional decisions, how automated feedback informs content explanations, and how ethical considerations shape the use of AI-generated insights. Through iterative refinement, these relationships were synthesised into a layered conceptual model that illustrates

how foundational knowledge domains interface with AI-enhanced pedagogical demands. The conceptual synthesis unfolded across three interconnected stages, each contributing to the gradual construction of the framework. The first stage involved a comprehensive review of scholarship on PK, CK, and TK in mathematics education. The second synthesised contemporary literature on AI in education, identifying four transversal competencies of data literacy, ethics, reflective and adaptive practice, and collaborative competence that extend beyond traditional TPACK constructs. The third stage integrated these findings into a unified conceptual framework that positions PK, CK, and TK as foundational, while situating transversal competencies as cross-cutting dimensions necessary for responsible and effective AI use. This integration was guided by empirical evidence and aligned with international policy recommendations to ensure ethical, pedagogically sound AI adoption.

Although empirical validation is not part of conceptual research, several strategies were employed to enhance conceptual validity. The use of diverse literature spanning mathematics pedagogy, AI integration, learning analytics, and teacher competence ensured comprehensive coverage of relevant constructs. Triangulation was achieved through the convergence of findings from empirical studies, systematic reviews, and policy frameworks. The iterative nature of the concept-mapping process strengthened internal coherence, while attention to global policy ensured external relevance and transferability across contexts. To enhance methodological transparency, Figure 1 presents a unique PRISMA-lite flow diagram that summarises the literature identification, screening, eligibility assessment, and synthesis process used to construct the conceptual framework.

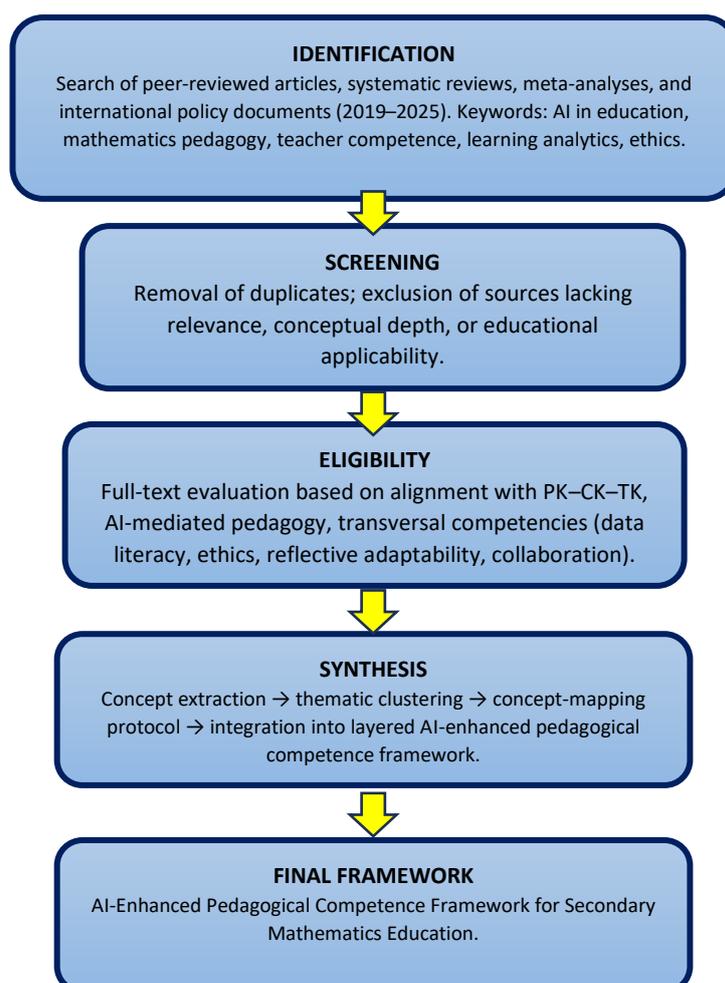


Figure 1: Flow diagram of the stage's framework building process

FINDINGS

The outcome of this conceptual study is a comprehensive framework for AI-enhanced pedagogical competence in secondary mathematics education. The framework builds upon the foundational knowledge domains of Pedagogical Knowledge (PK), Content Knowledge (CK), and Technological Knowledge (TK), while integrating a set of transversal competencies of data literacy and ethics, reflective–adaptive competence, and collaborative competence that are essential for functioning effectively in AI-rich instructional environments. These domains interact dynamically, forming a layered structure in which PK, CK, and TK function as core pillars and the transversal competencies operate as cross-cutting mechanisms that regulate, refine, and elevate teachers’ decision-making in AI-mediated classrooms.

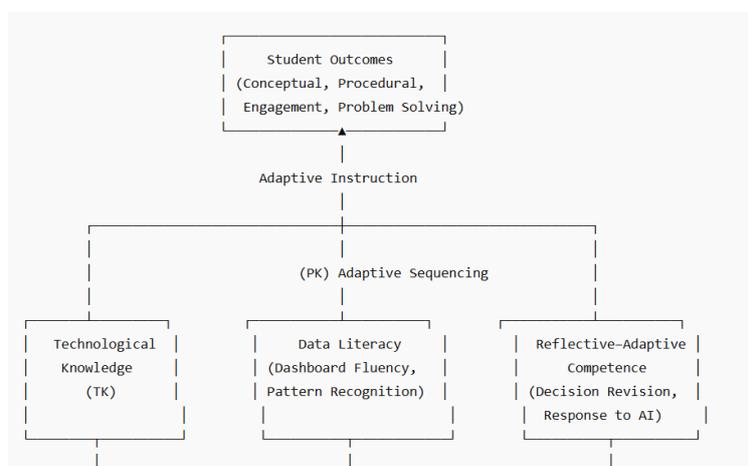
To strengthen conceptual clarity and support future empirical validation, each construct within the framework is defined operationally. Technological Knowledge (TK) refers to teachers’ capacity to operate AI-driven tools such as analytics dashboards, intelligent tutoring systems, adaptive platforms, and generative AI models. Pedagogical Knowledge (PK) encompasses teachers’ expertise in lesson design, adaptive task sequencing, differentiation, and orchestration of AI-mediated instructional strategies. Content Knowledge (CK) represents teachers’ understanding of mathematical concepts and their ability to employ AI-powered visualisations, simulations, and misconception-detection tools to enhance conceptual learning. Data literacy involves the interpretation, evaluation, and pedagogical application of AI-generated analytics including heatmaps, trend lines, and error clusters. Ethical AI competence reflects teachers’ ability to recognise and mitigate algorithmic bias, ensure data privacy, and adopt transparent and equitable AI practices. Reflective–adaptive competence describes teachers’ use of AI feedback to iteratively refine instructional decisions and evaluate the reliability and pedagogical relevance of AI recommendations. Collaborative competence refers to the effective use of AI-mediated communication and shared analytics to support alignment among teachers, school leaders, parents, and students. Table 1 summarises these domains, their core components, associated AI-enhanced dimensions, and the expected pedagogical outcomes in mathematics classrooms.

Table 1: Conceptual Framework of Components for AI-Enhanced Pedagogical Competence

Domain	Main Components	AI-Enhanced Dimensions	Expected outcome in Mathematic Teaching
Pedagogical Knowledge (PK)	Planning lessons, implementing instructional strategies, and managing the classroom	Lesson design informed by AI, adaptive sequencing of instruction, and real-time support in the classroom through chatbots and virtual agents	Enhanced instructional methods tailored to student requirements
Content Knowledge (CK)	Comprehensive grasp of secondary mathematical concepts	Content visualisation utilising AI, including dynamic graphing tools and simulations, alongside error-detection feedback mechanisms.	Improved conceptual understanding and correction of errors in student learning
Technological Knowledge (TK)	Utilisation of digital tools and platforms.	Dashboards utilising AI for analytics, systems for intelligent tutoring, and	Enhanced decision-making by educators via real-time insights

Data Literacy & Ethics	Analysing student advancement and equity.	automated assessment tools Interpretation of learning analytics, awareness of bias, and protection of data privacy	Adoption of responsible and ethical AI in educational settings
Reflective & Adaptive Competence	Ongoing professional development and reflective practice.	Artificial intelligence-based professional feedback, remote coaching, and recommendation systems for educational practices	.Educators modify strategies in an iterative manner informed by evidence
Collaborative Competence	Interacting with peers, parents, and policymakers	Communication tools enhanced by AI and shared analytics with stakeholders.	Enhanced collaboration and transparency regarding student progress

The framework highlights how foundational teacher knowledge and transversal competencies interact in shaping effective AI-mediated mathematics instruction. PK, CK, and TK remain indispensable, but their enactment is increasingly conditioned by AI tools. For example, PK is strengthened through AI-enabled adaptive sequencing and real-time feedback from chatbots and virtual agents. CK is enhanced through dynamic mathematical visualisations, automated error detection, and simulation-based explorations that make abstract concepts more accessible. TK expands from basic tool operation to include dashboard interpretation, system orchestration, and alignment of AI recommendations with lesson objectives. Transversal competencies deepen and regulate this process. Data literacy and ethics ensure that teachers can interpret analytics responsibly, safeguard student data, and identify algorithmic inequities (UNESCO, 2023; OECD, 2023). Reflective–adaptive competence enables teachers to respond thoughtfully to AI-generated insights, refining their pedagogy without relinquishing professional judgement (Ren, 2025). Collaborative competence supports shared understanding among stakeholders through AI-mediated communication tools, allowing transparent reporting of progress and more coordinated instructional planning (Ning, 2024). Together, these elements form an integrated conceptual model in which AI operates not as a replacement for teacher expertise but as a pedagogical partner that enhances lesson design, strengthens conceptual explanations, enriches decision-making quality, and deepens stakeholder engagement. Figure 2 visually represents the structure and directional relationships among these constructs.



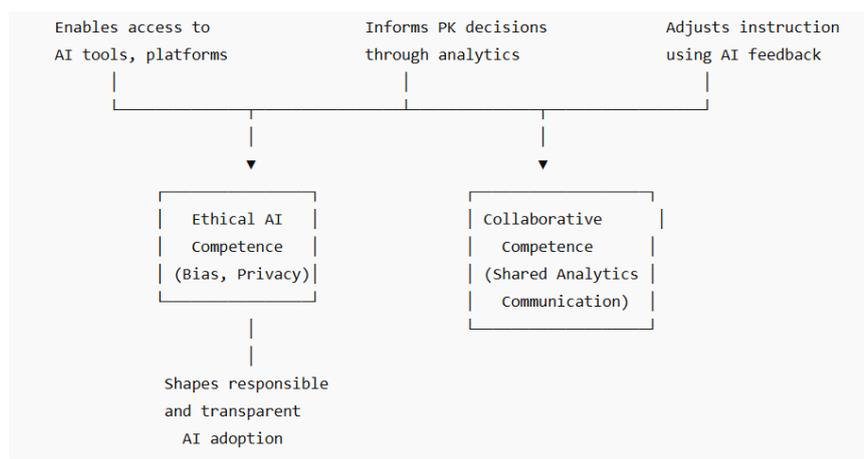


Figure 2: Conceptual framework for AI-Enhanced Pedagogical Competence in Secondary Mathematics Education

DISCUSSION

Foundational Knowledge Domains

The findings underscore the significance of Pedagogical Knowledge (PK), Content Knowledge (CK), and Technological Knowledge (TK) as foundational elements of mathematics teaching competence. Each of these domains is undergoing transformation due to artificial intelligence (AI). PK, traditionally centred on lesson planning, instructional strategies, and classroom management, has now evolved to incorporate AI-informed lesson design, adaptive sequencing, and real-time support mechanisms, including chatbots and virtual agents. These tools enhance the adaptability and responsiveness of teaching to meet student needs. CK, rooted in educators' proficiency in mathematical concepts, is likewise augmented by AI-driven tools. Dynamic graphing, simulations, and automated error-detection mechanisms enhance the accessibility of abstract content and provide immediate feedback on misconceptions (Schoenherr et al., 2024). Simultaneously, TK encompasses not only fundamental digital tool usage but also advanced practices, including the interpretation of analytics dashboards, management of intelligent tutoring systems, and application of automated assessments. This shift illustrates the capacity of AI to enhance teachers' ability to make informed instructional decisions via real-time insights (Son et al., 2024).

Transversal Competencies

The findings indicate that PK, CK, and TK alone are inadequate in AI-rich environments. Three transversal competencies—data literacy and ethics, reflective and adaptive competence, and collaborative competence—are essential for effective integration. Data literacy and ethics enable educators to interpret learning analytics in a responsible manner, protect student privacy, and confront algorithmic bias. Global education policy increasingly emphasises these capacities, with organisations like UNESCO (2023) and the OECD (2023) advocating for the ethical and transparent adoption of AI. Reflective and adaptive competence enables teachers to critically engage with AI-generated feedback, allowing for iterative refinement of pedagogical approaches while maintaining professional agency. The ongoing professional development, facilitated by AI-based coaching and recommendation systems, is crucial for maintaining innovation in practice (Ren, 2025). Collaborative competence acknowledges the relational aspect of teaching. AI-enhanced communication and shared analytics promote increased engagement

among peers, parents, and policymakers, thereby facilitating greater transparency and collective responsibility for student learning (Ning, 2024).

Ethics and Equity in Practice

While UNESCO (2023) and OECD (2023) emphasise the need for ethical, transparent, and equitable AI integration, operationalising these expectations at the school level requires concrete implementation guidelines. To support responsible AI use in secondary mathematics classrooms, the following School-Level AI Ethics and Equity Checklist provides practical steps for teachers, Heads of Department (HODs), and administrators. These steps ensure that AI integration follows a privacy-by-design approach, includes mechanisms for monitoring algorithmic fairness, and upholds transparency for students and parents.

School-Level AI Ethics & Equity Checklist

1. Privacy-by-Design Protocols

- Ensure all AI tools comply with Malaysia's PDPA and school data-protection rules.
- Disable unnecessary data collection (e.g., location, behavioural metadata).
- Store analytics on secure, school-approved platforms only.
- Apply role-based access controls so that student dashboards are accessible only to relevant teachers.

2. Algorithmic Bias and Fairness Checks

- Conduct monthly bias audits on AI-generated recommendations (e.g., difficulty level assignment, predictive performance labels).
- Compare analytics patterns across groups (gender, class, socioeconomic background) to detect inequitable patterns.
- Review ITS explanation logs to ensure that automated feedback is consistent across student profiles.
- Establish a process where flagged discrepancies trigger teacher review rather than automated reinforcement.

3. Transparency and Communication

- Provide parents with a **Transparency Note** outlining:
 - AI tools used in mathematics learning
 - What data is collected and why
 - How student privacy is protected
 - How AI will (and will not) influence assessment
- Prepare student-friendly information sheets explaining AI recommendations, chatbot guardrails, and data rights.

4. Student and Parent Opt-Out Mechanisms

- Offer alternative non-AI learning pathways for families who prefer not to participate.
- Ensure students who opt out are not disadvantaged in grading, access to materials, or teacher feedback.

- Create a secure logging system documenting opt-out requests and corresponding instructional accommodations.

5. Classroom-Level Ethical Protocols

- Activate safety filters and teacher-controlled guardrails on chatbots and generative AI tutors.
- Prohibit AI systems from making high-stakes decisions (e.g., grading, placement).
- Require teacher verification for all AI-generated explanations before use in class.
- Integrate short reflective prompts for students to critique AI outputs, promoting digital and mathematical reasoning.

Expected Outcomes

The interplay between foundational knowledge and transversal competencies yields notable results in mathematics education. Educators are equipped to provide adaptive and personalised instruction suited to a variety of learners. AI-driven visualisation and simulation tools enhance conceptual clarity, thereby improving student comprehension of abstract mathematics. Simultaneously, real-time analytics enhance teachers' decision-making, facilitating timely interventions that improve learning outcomes. The framework emphasises responsible and ethical AI use, promoting fairness and transparency in educational practices (UNESCO, 2023; Williamson & Eynon, 2020). Reflective practice is essential, as educators consistently assess and modify their teaching methods with the assistance of AI insights. Collaborative engagement with stakeholders enhances accountability and fosters shared responsibility in the teaching and learning process.

AI as a Pedagogical Partner

The findings indicate that AI should be viewed not as a replacement for teacher expertise, but rather as a collaborative educational tool. AI enhances the teacher's capacity to create adaptive lessons, elucidate mathematical concepts, and make data-driven instructional choices, while simultaneously promoting ethical responsibility, reflective practice, and collaboration. This framework illustrates that successful AI integration requires the maintenance of foundational domains alongside the development of transversal competencies. AI enhances teacher expertise, ensuring that mathematics education is adaptive and human-centred within complex digital learning environments.

Suggestions and Implications

AI Integration Roadmap for Secondary Mathematics Education

The following roadmap operationalises the AI-Enhanced Pedagogical Competence Framework by translating core competencies into concrete actions for teachers, Heads of Department, school leaders, and district policymakers. It includes suggested timelines and minimal resource requirements to support feasible and sustainable AI adoption.

Table 2. Role-Specific Actions, Suggested Timelines, and Minimum Resource Requirements

Role	Key Actions Aligned to Framework	Timeline	Minimum Resources Needed
Teachers	- Incorporate AI analytics into lesson planning (misconception trends, task difficulty patterns).	Short-term (0–6 months)	- Access to ITS dashboards

Head of Department (HOD) / Mathematics Coach	<ul style="list-style-type: none"> - Configure chatbot/ITS guardrails (stepwise hints only; no full solutions). - Conduct mini bias-checks during assessments. - Use AI dashboards to design targeted re-teaching for algebra, functions, and graphing. - Develop department-wide AI integration SOPs. - Lead monthly analytics calibration meetings. - Monitor consistency of AI-supported lesson design across teachers. - Support peer coaching on data interpretation and ethical AI use. - Establish school-level privacy-by-design policy. 	Medium-term (6–12 months)	<ul style="list-style-type: none"> - Basic AI literacy modules - Secure device and internet access - Time allocation for PLCs - Data-sharing protocols - Access to comparative analytics across classes
Principal / School Leadership	<ul style="list-style-type: none"> - Approve AI tools meeting ethical & curriculum alignment standards. - Communicate transparency notes to parents and set up opt-out procedures. - Allocate resources for teacher training and infrastructure. - Develop national/state AI competency standards for mathematics teachers. 	Medium-term (6–12 months)	<ul style="list-style-type: none"> - Budget for tools & training - Technical support - Parent communication channels
District / Policy Level	<ul style="list-style-type: none"> - Provide validated AI tools that comply with privacy & fairness guidelines. - Conduct annual audits of algorithmic bias. - Ensure equity of access across rural/urban schools. 	Long-term (12–24 months)	<ul style="list-style-type: none"> - Policy frameworks & governance mechanisms - Funding models - Data infrastructure for secure district-wide analytics

Synthesis

Collectively, this roadmap operationalises the framework by translating competencies into actionable steps at classroom, departmental, leadership, and policy levels. By providing clear timelines and minimal resource requirements, the roadmap ensures that AI integration progresses in a structured, ethical, and equitable manner, supporting sustainable and context-responsive improvements in secondary mathematics teaching.

CONCLUSION

This research contributes to mathematics education by introducing a conceptual framework for the integration of AI in enhancing pedagogical competence within secondary mathematics instruction. The framework builds upon the established domains of Pedagogical Knowledge (PK), Content Knowledge (CK), and Technological Knowledge (TK), enhancing teacher expertise through transversal competencies such as data literacy and ethics, reflective and adaptive competence, and collaborative

competence. The findings demonstrate that PK, CK, and TK are essential for effective teaching, yet their application in AI-enhanced environments is increasingly influenced by intelligent systems, adaptive platforms, and real-time analytics. The discussion underscores the interaction between foundational knowledge and transversal competencies, asserting that AI integration should enhance teacher expertise rather than replace human judgement with machine outputs, through adaptive, ethical, and collaborative practices. Teachers are seen as proactive individuals who utilise AI to create more tailored lessons, offer clearer conceptual explanations, and enhance decision-making through real-time data support. The framework emphasises the ethical necessity of maintaining fairness, transparency, and reflective practice, thereby ensuring the teacher's central role in the digital classroom. The recommendations and implications arising from this framework indicate various pathways for practice, policy, and research. The framework offers a structured approach for teachers' professional development, emphasising ethical data utilisation, ongoing reflection, and collaborative engagement. It indicates the necessity of incorporating AI literacy and adaptive practices into teacher education and professional development curricula. The framework highlights the necessity of systemic support, governance structures, and ethical guidelines for policymakers and school leaders to facilitate AI adoption while preserving teacher agency. This provides researchers with a basis for empirical validation via longitudinal, mixed-methods, and cross-national studies to evaluate the manifestation of AI-enhanced competencies in practice and their effects on student learning outcomes.

The proposed framework enhances the discourse on AI in education by redefining pedagogical competence for the digital era. AI is positioned as a pedagogical partner that enhances the teacher's role, ensuring that technology aligns with the broader objectives of equity, transparency, and professional development. This study aligns theoretical innovation with practical recommendations, offering a conceptual roadmap and a call to action for educators, policymakers, and researchers addressing the opportunities and challenges of AI integration in mathematics education.

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DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

This manuscript utilised generative AI and AI-assisted technologies solely to support the writing and editorial process. OpenAI's ChatGPT (GPT-4) was used to refine language clarity, enhance coherence, and improve the organisation of sections such as the abstract, introduction, methodology, and conclusion. All substantive ideas, theoretical arguments, and conceptual insights were developed by the authors. The authors maintained full authority over the content, made all final decisions regarding phrasing and structure, and ensured the academic accuracy and integrity of all information presented. No AI tools were used for data analysis, theoretical construction, or the generation of original research findings.

LIMITATIONS OF THE CONCEPTUAL APPROACH

As a conceptual study, this research carries several methodological limitations. First, the proposed framework has not yet undergone empirical validation, and its practical applicability in classroom settings remains to be tested. Second, the analysis is based exclusively on secondary literature, which may not fully capture contextual variations or on-the-ground complexities faced by teachers integrating AI into mathematics instruction. Third, although a structured concept-mapping protocol guided the synthesis process, an inherent degree of subjectivity is unavoidable when selecting constructs, determining thematic boundaries, and interpreting relationships among domains. Finally, future research should empirically examine the framework through classroom studies, teacher

interviews, and mixed-method investigations to evaluate its robustness, refine its components, and establish its validity across diverse educational contexts.

Conflict of Interest: There are no conflicts of interest in this study

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