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Development of the SMART-TPACK Model: An AI-Integrated Instructional Framework for Enhancing Pre-Service Mathematics Teachers' Cognitive Competence

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ABSTRACT: The rapid advancement of artificial intelligence (AI) has reshaped mathematics teacher education, requiring pre-service teachers to integrate technological, pedagogical, and content knowledge within AI-supported learning environments. Although the Technological Pedagogical Content Knowledge (TPACK) framework has been widely adopted, existing studies have primarily emphasized competency assessment rather than developing validated instructional models that systematically integrate AI into mathematics teacher education. This study addresses this gap by developing and validating the SMART-TPACK (Systematic Model for AI-Responsive Teaching with TPACK) instructional model to enhance the mathematical cognitive competence of pre-service mathematics teachers. This study employed a Research and Development (R&D) approach consisting of needs analysis, model design, expert validation, model revision, limited implementation, and effectiveness testing. Data were collected through observations, interviews, document analysis, expert validation sheets, cognitive competency tests, classroom observations, and student response questionnaires. The effectiveness of the model was evaluated using a quasi-experimental design involving experimental and control groups. The findings indicate that the SMART-TPACK model is theoretically valid, practically feasible, and effective in improving students' mathematical cognitive competence. Students who learned using the SMART-TPACK model demonstrated substantially higher gains in AI-based technological knowledge, pedagogical integration, content knowledge, and AI–TPACK integration than those receiving conventional instruction. The large effect size further confirms the instructional effectiveness of the proposed model. This study contributes to mathematics teacher education by extending the TPACK framework into an AI-responsive instructional model that systematically integrates AI literacy within mathematics learning. The SMART-TPACK model provides an empirically validated framework that can support teacher educators and curriculum developers in preparing future mathematics teachers for AI-enhanced educational environments..

Keywords: artificial intelligence, cognitive competency, prospective mathematics teachers, SMART-TPACK.

***ABSTRAK**: Pesatnya kemajuan kecerdasan buatan (AI) telah mengubah wajah pendidikan guru matematika, yang menuntut calon guru untuk mengintegrasikan pengetahuan teknologi, pedagogi, dan materi pelajaran dalam lingkungan pembelajaran yang didukung AI. Meskipun kerangka kerja *Technological Pedagogical Content Knowledge (TPACK) telah diadopsi secara luas, penelitian yang ada selama ini lebih menekankan pada penilaian kompetensi daripada pengembangan model pembelajaran tervalidasi yang secara sistematis mengintegrasikan AI ke dalam pendidikan guru matematika. Penelitian ini menjawab kesenjangan tersebut dengan mengembangkan dan memvalidasi model pembelajaran SMART-TPACK (Systematic Model for AI-Responsive Teaching with TPACK) untuk meningkatkan kompetensi kognitif matematis calon guru matematika. Penelitian ini menggunakan pendekatan *Research and Development**

(R&D) yang mencakup analisis kebutuhan, perancangan model, validasi ahli, revisi model, implementasi terbatas, dan uji efektivitas. Data dikumpulkan melalui observasi, wawancara, analisis dokumen, lembar validasi ahli, tes kompetensi kognitif, observasi kelas, dan kuesioner respons mahasiswa. Efektivitas model dievaluasi menggunakan desain kuasi-eksperimen yang melibatkan kelompok eksperimen dan kelompok kontrol. Hasil penelitian menunjukkan bahwa model SMART-TPACK valid secara teoretis, layak secara praktis, dan efektif dalam meningkatkan kompetensi kognitif matematis mahasiswa. Mahasiswa yang belajar menggunakan model SMART-TPACK menunjukkan peningkatan yang jauh lebih tinggi dalam pengetahuan teknologi berbasis AI, integrasi pedagogis, pengetahuan materi pelajaran, dan integrasi AI-TPACK dibandingkan dengan mereka yang menerima pembelajaran konvensional. Besarnya ukuran efek (effect size) semakin memperkuat bukti efektivitas pembelajaran dari model yang diusulkan ini. Penelitian ini berkontribusi pada pendidikan guru matematika dengan memperluas kerangka kerja TPACK menjadi model pembelajaran yang responsif terhadap AI, yang secara sistematis mengintegrasikan literasi AI ke dalam pembelajaran matematika. Model SMART-TPACK menyediakan kerangka kerja yang tervalidasi secara empiris untuk mendukung pendidik guru dan pengembang kurikulum dalam mempersiapkan calon guru matematika masa depan menghadapi lingkungan pendidikan yang diperkaya oleh AI.

***Kata kunci**: calon guru matematika, kecerdasan buatan, kompetensi kognitif, SMART-TPACK.*

INTRODUCTION

The rapid advancement of Artificial Intelligence (AI) has fundamentally transformed educational systems worldwide, creating unprecedented opportunities and challenges for teacher education. AI technologies, including generative AI, intelligent tutoring systems, adaptive learning platforms, and learning analytics, have reshaped the ways teaching, learning, and assessment are designed and implemented. Consequently, teachers are expected not only to master disciplinary knowledge and effective pedagogical strategies but also to develop the competence to integrate AI ethically, critically, and pedagogically into classroom practice (Boumediene & Ouarniki, 2025; Oláh & Šimek, 2025; Salazar, 2025). This transformation has shifted the focus of teacher education from conventional digital literacy toward AI-responsive professional competencies that enable future teachers to design meaningful technology-enhanced learning environments.

These demands are particularly significant in mathematics education, where teaching requires the integration of conceptual understanding, mathematical reasoning, problem-solving, and multiple representations of abstract concepts. Recent studies indicate that AI has considerable potential to improve mathematics learning through adaptive feedback, personalized instruction, intelligent visualization, automated assessment, and data-informed instructional decision-making (Bilgin, 2025; Chetia, 2025; Shirzad & Darazi, 2025). Nevertheless, the successful implementation of these technologies depends largely on teachers' ability to integrate AI with appropriate pedagogical approaches and sound mathematical content knowledge rather than merely operating digital tools (Dueñas, 2025; Magalhães et al., 2025; Martínez & Escobar Gutierrez, 2025). Consequently, preparing pre-service mathematics teachers with

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AI-integrated instructional competencies has become an increasingly important priority for higher education institutions.

The Technological Pedagogical Content Knowledge (TPACK) framework has long been recognized as one of the most influential theoretical models for explaining teachers' competence in technology-enhanced instruction (Naranjo et al., 2025a; Zhang & Zhou, 2023) . TPACK proposes that effective teaching emerges from the dynamic interaction among technological knowledge, pedagogical knowledge, and content knowledge rather than from mastery of these domains independently. Numerous empirical studies have consistently demonstrated that stronger TPACK competencies are associated with more effective technology integration, higher instructional quality, and improved student learning outcomes (Martínez et al., 2024; Naranjo, 2024) Nevertheless, recent evidence also suggests that many pre-service teachers continue to experience difficulties in translating technological knowledge into authentic classroom practice, particularly when integrating emerging AI technologies into mathematics instruction (Martínez et al., 2024; Naranjo, 2024). These findings indicate that although TPACK provides a robust conceptual foundation for technology integration, it offers limited guidance regarding how AI competencies should be systematically cultivated through instructional design.

Recent developments in educational technology have therefore expanded the TPACK framework through the concepts of AI literacy and AI-TPACK. AI literacy extends beyond the technical ability to operate AI applications by encompassing the knowledge, critical thinking, ethical awareness, and pedagogical judgment required to use AI effectively and responsibly in educational contexts (Deb & Pradhan, 2023; Souza & Cardoso, 2024). Building upon this perspective, AI-TPACK integrates AI competencies into teachers' technological, pedagogical, and content knowledge, enabling teachers to design AI-supported learning experiences that are pedagogically meaningful (Mondragón, 2024; Martínez et al., 2024). Previous empirical studies consistently report positive relationships between AI literacy, digital competence, instructional innovation, and technology (Naranjo et al., 2025b; Pasmala et al., 2025). However, these studies predominantly conceptualize AI literacy as an individual competency to be measured rather than as a competency that can be systematically developed through validated instructional interventions.

Despite recent advances in AI-supported teacher education, three important research gaps remain. First, previous studies have mainly examined AI literacy and TPACK as individual competencies rather than as outcomes of systematically designed instructional interventions (Martínez et al., 2024; Pasmala et al., 2025). Second, existing AI–TPACK research has largely emphasized descriptive or correlational analyses, providing limited guidance on how AI can be integrated into coherent learning processes that progressively develop teachers' technological, pedagogical, and mathematical competencies (Naranjo et al., 2025b; Souza & Cardoso, 2024). Third, empirical evidence regarding validated AI-responsive instructional models for pre-service mathematics teachers remains scarce despite the distinctive cognitive demands of mathematics education (Deb

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& Pradhan, 2023; Zhang & Zhou, 2023). These limitations demonstrate the need for a validated instructional model that systematically integrates AI literacy within the TPACK framework to strengthen pre-service teachers' mathematical cognitive competence.

To address these limitations, this study develops the SMART-TPACK (Systematic Model for AI-Responsive Teaching with TPACK) instructional model using a Research and Development (R&D) approach. Unlike previous AI–TPACK studies that primarily evaluated teachers' competencies or readiness to use AI, this study develops and empirically validates an instructional model that systematically integrates AI literacy, technological knowledge, pedagogical knowledge, mathematical content knowledge, and reflective learning into a coherent instructional framework for mathematics teacher education. The model was subsequently validated through expert judgment and empirically evaluated to determine its effectiveness in improving the mathematical cognitive competence of pre-service mathematics teachers. Accordingly, the proposed model represents both a theoretical extension of the TPACK framework and a practical instructional innovation for AI-enhanced mathematics teacher education.

Therefore, this study aims to (1) develop and validate the SMART-TPACK instructional model, (2) examine its effectiveness in improving the mathematical cognitive competence of pre-service mathematics teachers, and (3) provide an empirically validated AI-responsive instructional framework that extends the TPACK theory through the systematic integration of AI literacy into mathematics teacher education. The findings are expected to contribute theoretically by enriching the emerging body of knowledge on AI-assisted teacher education and practically by providing evidence-based guidance for teacher educators, curriculum developers, and higher education institutions in preparing future mathematics teachers for increasingly AI-enhanced educational environments.

Accordingly, this study aims to develop and validate the SMART-TPACK instructional model, evaluate its effectiveness in improving the mathematical cognitive competence of pre-service mathematics teachers, and establish an integrated AI-responsive instructional framework for mathematics teacher education. The study contributes theoretically by extending the TPACK framework through the systematic integration of AI literacy and contributes practically by providing an empirically validated instructional model that can support teacher educators, curriculum developers, and higher education institutions in preparing future mathematics teachers for AI-enhanced learning environments

METHODS

Participants

This study involved pre-service mathematics teachers enrolled in the Mathematics Education Study Program at Pasundan University, Indonesia, during the 2025/2026 academic year. The participants were undergraduate students who were undertaking mathematics education courses designed to develop pedagogical, technological, and content knowledge relevant to future

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mathematics teaching. The population consisted of all students enrolled in the selected mathematics education course during the study period.

A purposive sampling technique was employed because the participants met the specific criteria required for the development and evaluation of the SMART-TPACK (Systematic Model for AI-Responsive Teaching with TPACK) instructional model. The inclusion criteria were: (1) enrollment in the selected mathematics education course during the study period, (2) completion of prerequisite courses in mathematics content, pedagogy, and educational technology, (3) attendance in all instructional sessions throughout the implementation of the SMART-TPACK model, and (4) completion of both pretest and posttest assessments. Students who did not complete all learning activities or failed to complete either assessment were excluded from the final analysis. The participants ranged in age from 25 to 35 years and represented adult learners preparing for professional careers as mathematics teachers. This age range reflects the typical characteristics of students enrolled in the Mathematics Education Study Program during the study period

The effectiveness testing involved two intact classes consisting of 60 pre-service mathematics teachers. One class (n = 30) served as the experimental group and received instruction using the SMART-TPACK instructional model, whereas the other class (n = 30) served as the control group and received conventional instruction. The two classes followed the same curriculum, were enrolled in the same academic semester, and possessed comparable academic backgrounds, thereby reducing potential confounding variables during the effectiveness evaluation. Purposive sampling was considered appropriate because the study aimed to evaluate the SMART-TPACK instructional model among participants who possessed relatively homogeneous academic backgrounds and had completed the prerequisite coursework necessary for AI-supported mathematics instruction.

For the model development stage, expert validation was conducted by three specialists comprising one mathematics education expert, one educational technology expert, and one Artificial Intelligence in Education expert. These experts were purposively selected based on their academic qualifications, research expertise, and experience in curriculum development and instructional innovation. Their evaluations focused on the theoretical relevance, internal consistency, instructional feasibility, clarity of instructional syntax, support system, reaction principles, and expected instructional impacts of the SMART-TPACK model. Table 1 presents the demographic characteristics of the participants involved in the effectiveness testing.

Table 1. Demographic Characteristics of Participants (n = 60).

Variable	Category	Experimental (n = 30)	Control (n = 30)	Total
Gender	Female	24	22	46
	Male	6	8	14
Academic Year	Third Year	30	30	60
Completed Mathematics Content Courses	Yes	30	30	60

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Completed Educational Technology Courses	Yes	30	30	60
Completed Mathematics Pedagogy Courses	Yes	30	30	60

All participants had completed prerequisite coursework in mathematics content, mathematics pedagogy, and educational technology before participating in the study. Consequently, they possessed relatively comparable prior knowledge and were considered suitable participants for evaluating the effectiveness of the SMART-TPACK instructional model in mathematics teacher education. No participant withdrew from the study during the implementation phase. Consequently, data from all 60 participants were included in the final statistical analyses, ensuring complete pretest–posttest data for both the experimental and control groups.

Research Design and Procedures

The SMART-TPACK instructional model was developed using the ADDIE instructional design framework, which consists of five interconnected stages: Analysis, Design, Development, Implementation, and Evaluation (Branch, 2009). The ADDIE framework was selected because it provides a systematic and iterative process for developing educational innovations through continuous refinement, expert validation, classroom implementation, and effectiveness evaluation. In this study, each phase generated outputs that served as the foundation for the subsequent phase, ensuring that the final instructional model was theoretically grounded, empirically validated, and pedagogically applicable. Figure 1 illustrates the overall research procedure adopted in this study.

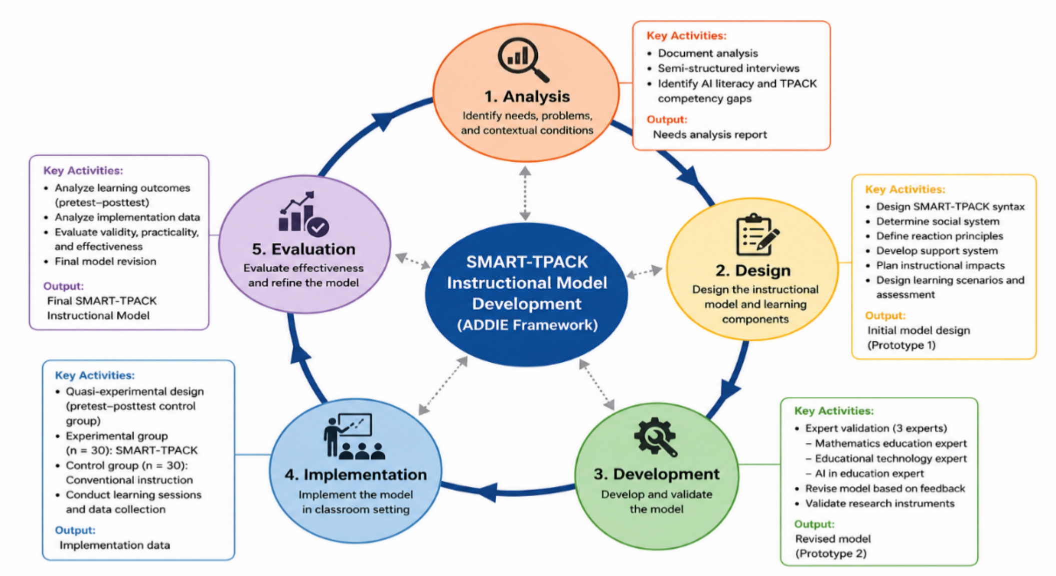

Figure 1. Reseacrh procedure for developing and evaluating the SMART-TPACK instructional model base on the ADDIE framework

Phase 1: Analysis

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The analysis phase was conducted to identify instructional problems, competency needs, and contextual challenges associated with integrating Artificial Intelligence (AI) into mathematics teacher education. Data were collected through document analysis and semi-structured interviews. The document analysis examined curriculum documents, course learning outcomes, semester learning plans, and other instructional documents to identify the expected competencies for prospective mathematics teachers. Semi-structured interviews were conducted with lecturers responsible for mathematics education courses to explore existing instructional practices, challenges in integrating AI into mathematics learning, and the competencies required for future mathematics teachers. The findings from this phase formed the empirical foundation for designing the SMART-TPACK instructional model.

Phase 2: Design

Based on the findings obtained during the analysis phase, the SMART-TPACK instructional model was designed by integrating Artificial Intelligence Literacy with the Technological Pedagogical Content Knowledge (TPACK) framework. The design process involved formulating the instructional syntax, defining the social system, principles of reaction, support system, instructional impacts, and accompanying learning materials. Learning objectives, lesson scenarios, assessment instruments, and supporting instructional resources were also developed to ensure alignment between the proposed model and the intended learning outcomes.

Phase 3: Development

The initial prototype of the SMART-TPACK instructional model and its supporting instruments underwent expert validation to evaluate their theoretical consistency, instructional feasibility, content relevance, and practical applicability. The validation process involved three experts consisting of a mathematics education expert, an educational technology expert, and an Artificial Intelligence in Education expert. Each expert independently reviewed the model using structured validation instruments and provided qualitative suggestions for improvement. Revisions were subsequently made based on the validators' recommendations to produce a refined version of the instructional model prior to classroom implementation.

Phase 4: Implementation

Following expert validation and revision, the SMART-TPACK instructional model was implemented using a quasi-experimental pretest-posttest control group design. Two intact classes were purposively selected to participate in the effectiveness evaluation. The experimental group (n = 30) received instruction using the SMART-TPACK instructional model, whereas the control group (n = 30) received conventional mathematics instruction. Both groups completed equivalent pretests before the intervention and posttests following the completion of the instructional program. The implementation was conducted

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under comparable instructional conditions to ensure the validity of the effectiveness comparison.

Phase 5: Evaluation

The evaluation phase examined both the quality of the developed instructional model and its effectiveness in improving students' mathematical cognitive competence. Formative evaluation was conducted throughout the development process through expert validation and iterative revisions, while summative evaluation was performed following classroom implementation. Quantitative evaluation included analyses of students' learning outcomes using pretest-posttest scores, whereas qualitative feedback obtained during implementation was used to refine the instructional model. The findings from this phase were used to determine the validity, practicality, and effectiveness of the SMART-TPACK instructional model as a learning innovation for mathematics teacher education.

The five ADDIE phases resulted in the development of the SMART-TPACK instructional model, which integrates Artificial Intelligence (AI) literacy with the Technological Pedagogical Content Knowledge (TPACK) framework to enhance pre-service mathematics teachers' mathematical cognitive competence. The conceptual relationships among the major components of the model are illustrated in Figure 2.

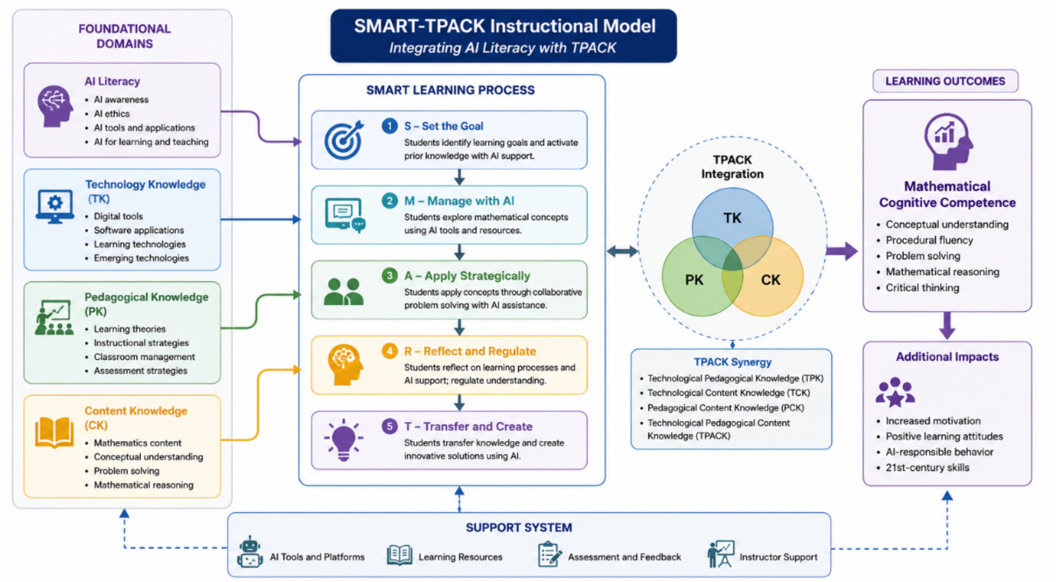

Figure 2. Conceptual framework of the SMART-TPACK instructional model

Figure 2 illustrates the conceptual foundation of the SMART-TPACK instructional model. The model is built upon four foundational domains, namely AI Literacy, Technological Knowledge, Pedagogical Knowledge, and Content Knowledge. These domains are integrated through the SMART learning process, enabling prospective mathematics teachers to develop comprehensive TPACK competencies that ultimately enhance their mathematical cognitive competence. The model is further supported by AI-assisted learning resources, instructional

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support systems, and continuous assessment to facilitate meaningful learning experiences.

Research Instruments

Multiple research instruments were employed to support the development, validation, implementation, and evaluation of the SMART-TPACK instructional model. The instruments were designed to collect both qualitative and quantitative data corresponding to the objectives of each ADDIE phase.

During the Analysis phase, document analysis sheets and semi-structured interview guides were used to identify instructional needs, curriculum requirements, and challenges related to the integration of Artificial Intelligence (AI) in mathematics teacher education. The document analysis focused on curriculum documents, semester learning plans, and course learning outcomes, while the interviews explored lecturers' perceptions regarding instructional practices, students' learning needs, and AI integration in mathematics learning.

During the Development phase, a model validation sheet was employed to evaluate the quality of the SMART-TPACK instructional model. The validation instrument assessed six major components of the instructional model, namely: (1) theoretical foundation, (2) instructional syntax, (3) social system, (4) principles of reaction, (5) support system, and (6) instructional and accompanying impacts. The instrument also provided space for qualitative feedback and recommendations from the expert validators.

The effectiveness of the SMART-TPACK instructional model was evaluated during the Implementation and Evaluation phases using a mathematical cognitive competence test. The test consisted of essay and problem-solving items designed to measure students' conceptual understanding, procedural fluency, mathematical reasoning, and problem-solving ability. The same instrument was administered as both a pretest and posttest to the experimental and control groups.

In addition, an observation sheet was used to evaluate the implementation fidelity of the SMART-TPACK instructional model during classroom instruction. Observations focused on the consistency of instructional activities with the model syntax, student engagement, learning interactions, and classroom management. Student response questionnaires were also administered following implementation to obtain participants' perceptions regarding the practicality and usefulness of the instructional model. Table 2 summarizes the research instruments employed throughout the study.

Tabel 2. Research Instrument

Instrument	Purpose	Respondents/ Data Source	Main Indicators
Document Analysis Sheet	Needs analysis	Curriculum documents, lesson plans	Curriculum alignment, AI integration, learning outcomes

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Semi-Structured Interview Guide	Needs analysis	Mathematics education lecturers	Learning challenges, AI integration, competency needs
Expert Validation Sheet	Model validation	Three expert validators	Theoretical foundation, syntax, social system, reaction principles, support system, instructional impacts
Mathematical Cognitive Competence Test	Effectiveness evaluation	Students	Conceptual understanding, procedural fluency, reasoning, problem solving
Observation Sheet	Implementation fidelity	Classroom learning process	Syntax implementation, student participation, instructional management
Student Response Questionnaire	Practicality evaluation	Students	Ease of use, engagement, usefulness, satisfaction

The research instruments were developed based on the theoretical framework of AI Literacy, TPACK, instructional model development theory, and mathematics education literature. Prior to implementation, all instruments underwent expert review to evaluate content relevance, clarity, and representativeness before being used in the field trial.

Instrument Validity and Reliability

Prior to implementation, all research instruments underwent a content validation process to ensure their relevance, clarity, and consistency with the objectives of the study. Content validity was established through a Content Validity Assessment (CVA) conducted by three expert validators consisting of a mathematics education expert, an educational technology expert, and an Artificial Intelligence in Education expert. The validators evaluated each instrument in terms of content relevance, language clarity, construct appropriateness, and suitability for measuring the intended variables. Suggestions and recommendations provided during the validation process were incorporated to improve both the instructional model and the research instruments before field implementation.

The student response questionnaire was subsequently subjected to reliability testing to examine its internal consistency. Reliability analysis was conducted using Cronbach's Alpha coefficient. The questionnaire obtained a Cronbach's Alpha value of 0.956, indicating excellent internal consistency and confirming that the instrument was highly reliable for collecting students' responses toward the implementation of the SMART-TPACK instructional model. According to commonly accepted reliability criteria, Cronbach's Alpha values

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above 0.90 indicate excellent reliability, demonstrating that the questionnaire items consistently measured the intended construct.

The mathematical cognitive competence test, observation sheet, interview guide, and document analysis sheet were not subjected to Cronbach's Alpha analysis because they served different methodological purposes. The mathematical cognitive competence test was developed based on the learning objectives and validated through expert review to ensure content relevance, whereas the qualitative instruments were designed to facilitate data collection during the Analysis and Evaluation phases of the ADDIE model. Therefore, their quality was established primarily through expert judgment and content validation rather than internal consistency analysis.

Data Collection Procedure

Data collection was conducted systematically following the five phases of the ADDIE instructional design model. Each phase generated specific data that informed the subsequent stage of the development process, ensuring that the SMART-TPACK instructional model was developed based on empirical evidence and evaluated comprehensively.

The data collection process commenced with the Analysis phase. At this stage, document analysis and semi-structured interviews were conducted to identify instructional needs, curriculum requirements, and challenges associated with integrating Artificial Intelligence (AI) into mathematics teacher education. The document analysis focused on curriculum documents, course learning outcomes, semester learning plans, and instructional materials, while interviews with mathematics education lecturers explored existing instructional practices, AI integration, and competency needs for prospective mathematics teachers.

During the Design and Development phases, the findings from the needs analysis were used to construct the initial SMART-TPACK instructional model and its supporting learning instruments. The prototype was subsequently evaluated through expert validation involving three specialists in mathematics education, educational technology, and Artificial Intelligence in Education. Recommendations provided by the validators were used to revise and refine both the instructional model and the research instruments prior to classroom implementation.

The Implementation phase involved two intact classes consisting of an experimental group (n = 30) and a control group (n = 30). Before the instructional intervention, both groups completed a pretest measuring mathematical cognitive competence. The experimental group then participated in learning activities using the SMART-TPACK instructional model, whereas the control group received conventional instruction covering the same learning objectives. Upon completion of the instructional intervention, both groups completed an equivalent posttest to measure learning achievement.

The Evaluation phase consisted of formative and summative evaluation activities. Formative evaluation was conducted throughout the development process through expert validation and iterative revisions of the instructional model. Summative evaluation was performed after classroom implementation by

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analyzing students' pretest and posttest scores, classroom observation results, and student response questionnaires. These data were used to determine the validity, practicality, and effectiveness of the SMART-TPACK instructional model as an instructional innovation for mathematics teacher education. The overall data collection procedure employed in this study is summarized in Figure 3.

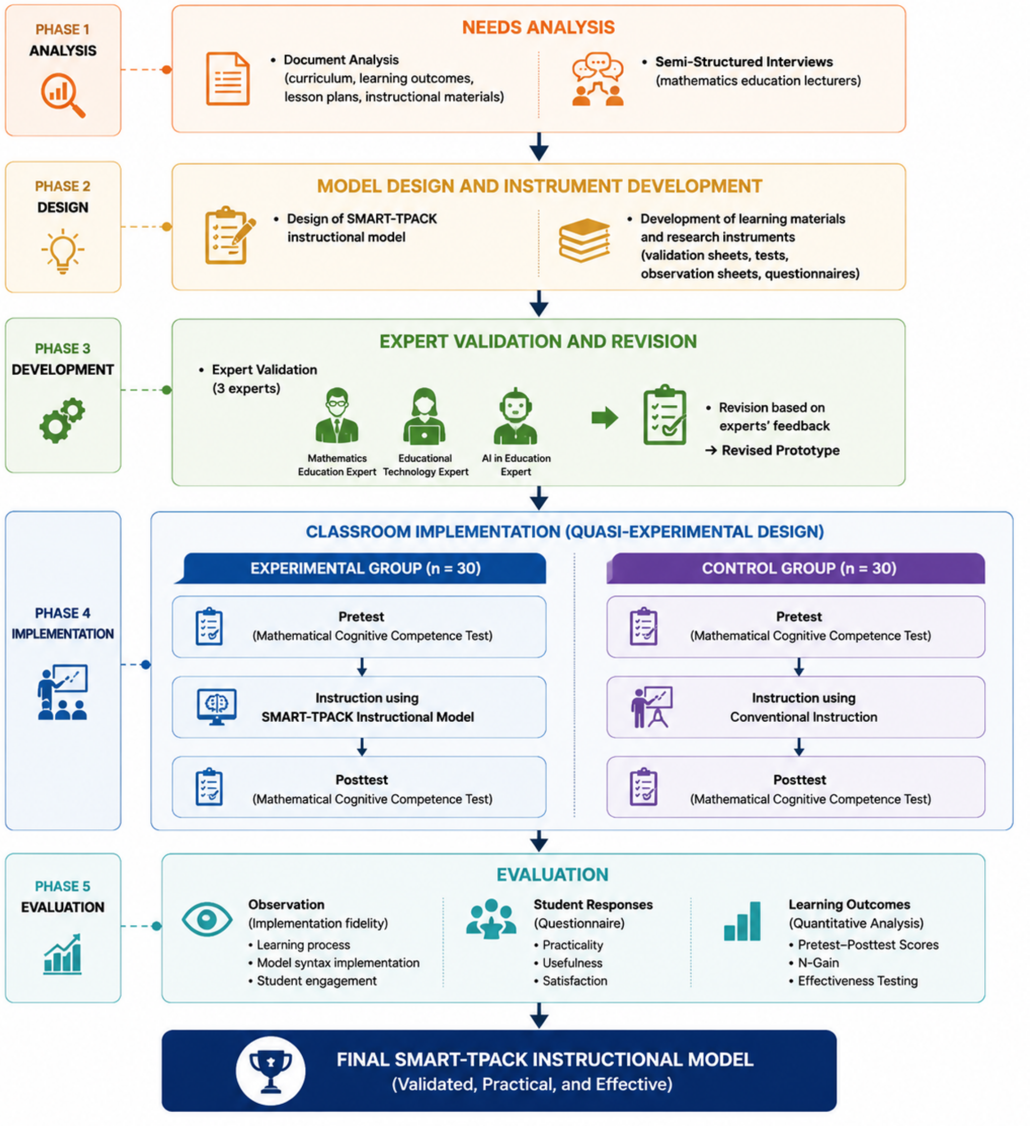

Figure 3. Data collection procedure of the study

Data Analysis

Both qualitative and quantitative data were analyzed to address the research objectives of developing, validating, and evaluating the SMART-TPACK instructional model. The selection of analytical techniques was aligned with the characteristics of the data collected during each phase of the ADDIE instructional design framework.

Qualitative data obtained during the Analysis phase, including document analysis and semi-structured interviews, were analyzed using thematic analysis. The analysis involved data reduction, coding, categorization, and interpretation to

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identify instructional needs, existing challenges, and competency requirements related to Artificial Intelligence (AI) integration in mathematics teacher education. The qualitative findings served as the empirical basis for designing the SMART-TPACK instructional model.

Quantitative data obtained during the Development phase were analyzed descriptively to summarize the results of expert validation and instrument evaluation. Suggestions and recommendations provided by the expert validators were synthesized and incorporated into the revision of the instructional model and supporting research instruments.

The effectiveness of the SMART-TPACK instructional model was evaluated using quantitative statistical analyses performed with IBM SPSS Statistics version 24. Prior to hypothesis testing, the assumptions of normality and homogeneity of variance were examined using the Shapiro–Wilk test and Levene's Test, respectively. These preliminary analyses were conducted to determine whether the data satisfied the assumptions required for parametric statistical testing.

To examine learning improvement within each group, paired-samples t-tests were conducted to compare students' pretest and posttest scores. Differences in learning outcomes between the experimental and control groups were analyzed using independent-samples t-tests. Furthermore, the magnitude of students' learning improvement was evaluated using the normalized gain (N-gain) index, which categorizes learning gains into low, moderate, and high improvement levels.

All statistical analyses were conducted at a significance level of $\alpha = 0.05$. The combination of thematic analysis, descriptive analysis, and inferential statistical procedures enabled comprehensive evaluation of the SMART-TPACK instructional model from the perspectives of instructional needs, expert validation, and learning effectiveness.

Table 3. Data Analysis Procedures

Research Objective	Data Source	Analysis Technique	Purpose
Identify instructional needs	Documents, interviews	Thematic analysis	Identify instructional problems and competency needs
Validate SMART-TPACK model	Expert validation sheets	Descriptive analysis	Determine content validity and revise the model
Test data assumptions	Pretest and posttest scores	Shapiro–Wilk test, Levene's Test	Assess normality and homogeneity
Examine within-group improvement	Pretest–posttest scores	Paired-samples *t*-test	Determine learning improvement within each group
Compare learning outcomes	Experimental and control groups	Independent-samples *t*-test	Evaluate differences between groups

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Measure learning improvement	Pretest–posttest scores	N-gain analysis	Determine the magnitude of learning gains

Ethical Considerations

Prior to the commencement of the study, permission to conduct the research was obtained from the Faculty of Teacher Training and Education and the Mathematics Education Study Program at Pasundan University, Indonesia. The research was carried out in accordance with institutional regulations governing educational research involving university students.

All participants were informed about the objectives, procedures, expected benefits, and duration of the study before data collection began. Participation was entirely voluntary, and students were assured that their decision to participate or withdraw from the study would not influence their academic standing or course assessment. Written informed consent was obtained from all participants before the implementation of the study.

To ensure research integrity and participant privacy, all collected data were treated confidentially and used exclusively for academic and research purposes. Participants' identities were anonymized during data processing and reporting, and only aggregated results are presented in this article. The researchers adhered to the principles of voluntary participation, confidentiality, and responsible data management throughout all stages of the research process. The study was conducted under the official research permission issued by the Faculty of Teacher Training and Education, Pasundan University.

RESULT AND DISCUSSION

Findings from the Analysis Phase

The Analysis phase was conducted to identify instructional needs, existing learning practices, and competency gaps related to the integration of Artificial Intelligence (AI) in mathematics teacher education. Data were obtained through document analysis and semi-structured interviews with three mathematics education lecturers. The document analysis included Course Learning Outcomes (CPMK), Semester Learning Plans (RPS), the Outcome-Based Education (OBE) curriculum, teaching materials, and course modules. These data sources provided a comprehensive understanding of the current instructional context and served as the empirical foundation for developing the SMART-TPACK instructional model.

The document analysis revealed that the curriculum had explicitly emphasized the development of pedagogical competence, mathematical content knowledge, and technology integration. However, explicit learning outcomes related to AI literacy and the pedagogically meaningful use of AI tools were not yet systematically incorporated into the curriculum documents. Although technology was recognized as an important component of mathematics teacher education, its implementation remained primarily focused on the use of presentation software and learning management systems, with limited emphasis on AI-supported instructional practices.

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The interview findings further confirmed these observations. The three lecturers consistently reported that pre-service mathematics teachers demonstrated adequate technological skills for accessing digital learning resources; however, they experienced difficulties in integrating AI into instructional planning and mathematics learning activities. AI applications were generally used for information retrieval rather than for facilitating conceptual understanding, generating multiple mathematical representations, providing adaptive feedback, or supporting mathematical reasoning. Furthermore, the lecturers indicated that many students tended to use digital technologies as supplementary tools instead of integrating them meaningfully with pedagogical strategies and mathematical content.

A synthesis of the qualitative findings identified three major instructional needs. First, prospective mathematics teachers required stronger AI literacy to effectively utilize AI technologies in mathematics learning. Second, there was a need for an instructional framework that systematically integrated Artificial Intelligence with the Technological Pedagogical Content Knowledge (TPACK) framework rather than treating technology as an isolated component of instruction. Third, learning activities needed to promote higher-order thinking, collaborative problem solving, reflective practice, and responsible use of AI to support meaningful mathematics learning.

To synthesize the findings obtained from document analysis and lecturer interviews, the major instructional needs identified during the Analysis phase are summarized in Figure 4.

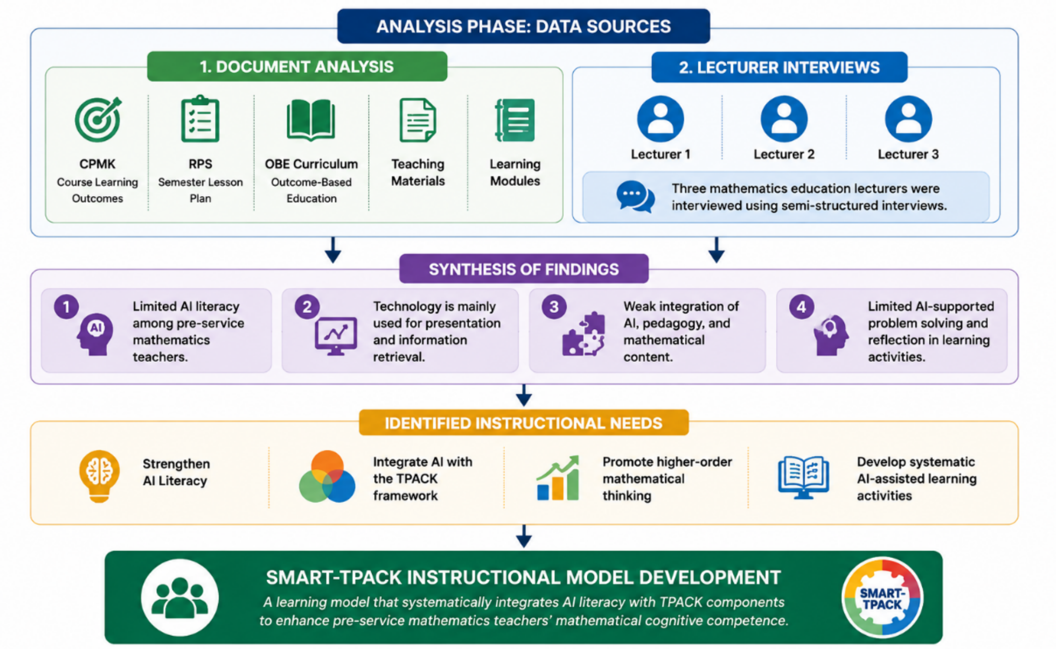

Figure 4. Synthesis of Needs Analysis Underpinning the Development of the SMART-TPACK Instructional Model

Figure 4 illustrates the logical progression from the needs analysis to the development of the SMART-TPACK instructional model. The synthesis of

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document analysis and lecturer interviews identified four major issues, namely limited AI literacy, technology use primarily for presentation and information retrieval, weak integration of AI with pedagogy and mathematical content, and limited AI-supported problem-solving activities. These findings led to the identification of four instructional needs that subsequently informed the design of the SMART-TPACK instructional model. Table 4 summarizes the major findings obtained during the Analysis phase.

Table 4. Summary of Instructional Needs Identified During the Analysis Phase

Data Source	Major Findings	Implications for SMART-TPACK Development
CPMK	Learning outcomes emphasized pedagogical, technological, and mathematical competencies but did not explicitly include AI literacy.	AI literacy was incorporated as a fundamental component of the instructional model.
RPS	Technology integration was present but primarily limited to conventional digital tools.	Learning scenarios were redesigned to integrate AI-supported instructional activities.
OBE Curriculum	Graduate competencies highlighted digital competence but lacked explicit AI-related competencies.	AI-supported competencies were aligned with existing graduate learning outcomes.
Teaching Materials and Modules	Learning resources contained limited AI-based activities and authentic problem-solving tasks.	AI-assisted learning resources and authentic mathematical tasks were developed.
Lecturer Interviews	Students experienced difficulties integrating AI with pedagogy and mathematical content.	The SMART-TPACK model was designed to systematically integrate AI Literacy with TPACK components.

The findings from the Analysis phase demonstrate that although technology integration had become part of mathematics teacher education, the pedagogically meaningful use of Artificial Intelligence remained limited. These findings provided the empirical justification for developing the SMART-TPACK instructional model as an instructional innovation that systematically integrates AI literacy with the TPACK framework to enhance prospective mathematics teachers' mathematical cognitive competence.

Design of the SMART-TPACK Instructional Model

The findings obtained during the Analysis phase served as the foundation for designing the SMART-TPACK instructional model. The model was developed to systematically integrate Artificial Intelligence (AI) literacy with the Technological

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Pedagogical Content Knowledge (TPACK) framework in order to enhance pre-service mathematics teachers' mathematical cognitive competence. The design process emphasized not only the integration of technology into mathematics instruction but also the pedagogically meaningful use of AI to support conceptual understanding, problem solving, collaboration, and reflective learning.

Based on the identified instructional needs, the SMART-TPACK instructional model was designed as a structured learning model consisting of four sequential learning stages. Each stage was developed to facilitate the progressive development of AI literacy, pedagogical competence, technological competence, and mathematical content knowledge within authentic learning situations. The conceptual structure of the SMART-TPACK instructional model is presented in Figure 5.

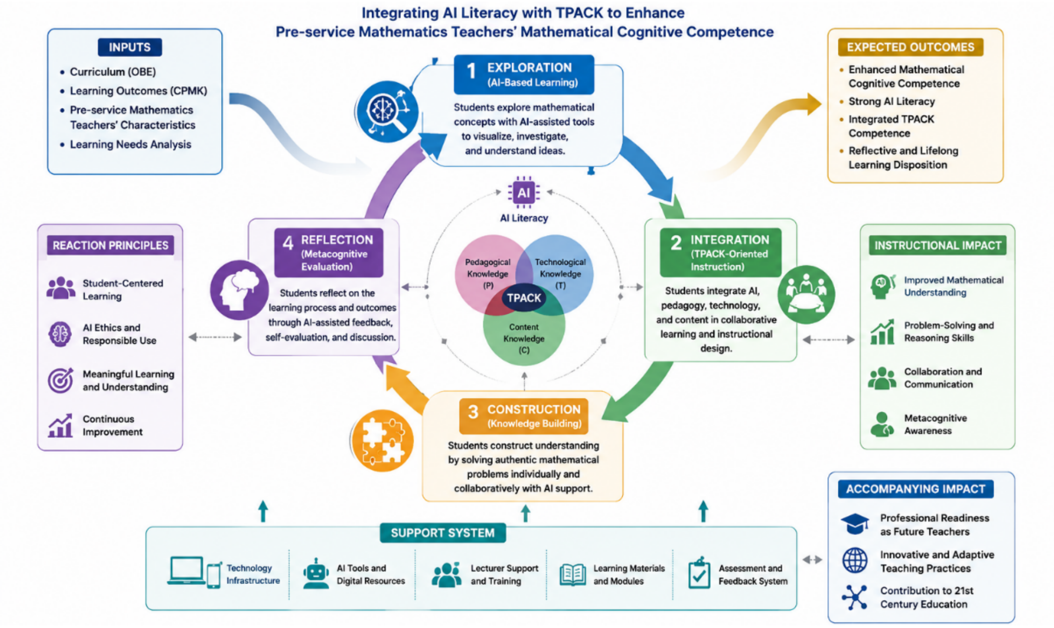

Figure 5. The SMART-TPACK Instructional Model

Figure 5 illustrates that the SMART-TPACK instructional model is grounded in the integration of AI Literacy and the TPACK framework. Learning begins with AI-supported exploration of mathematical concepts, followed by collaborative integration of technological, pedagogical, and mathematical knowledge. Students subsequently construct mathematical understanding through problem-solving activities and conclude the learning cycle with reflective evaluation supported by AI-assisted feedback. The four instructional stages are designed to function as an integrated learning process that gradually develops students' mathematical cognitive competence. The instructional characteristics of each stage are summarized in Table 5.

Table 5. Components of the SMART-TPACK Instructional Model

Stage	AI Function	Lecturer Role	Student Role
Exploration	Concept visualization, information retrieval	Facilitator	Explore concepts

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Integration	AI-assisted lesson planning	Coach	Integrate TPACK
Construction	AI-assisted problem solving	Guide	Construct knowledge
Reflection	AI feedback	Reflective facilitator	Self-evaluation

The Design phase produced a coherent instructional model that integrates AI literacy with TPACK principles into a systematic learning process. The resulting SMART-TPACK instructional model became the prototype subjected to expert validation during the subsequent Development phase.

Validation of the SMART-TPACK Instructional Model

The initial prototype of the SMART-TPACK instructional model, developed during the Design phase, was subjected to expert validation before classroom implementation. The validation process aimed to examine the model's theoretical soundness, instructional feasibility, practical applicability, and alignment with the integration of Artificial Intelligence (AI) and the Technological Pedagogical Content Knowledge (TPACK) framework. The evaluation was conducted by three experts representing the fields of mathematics education, educational technology, and Artificial Intelligence in Education.

Each validator independently assessed the instructional model using a structured validation instrument consisting of six dimensions: theoretical foundation, learning syntax, social system, principles of reaction, support system, and instructional and accompanying impacts. In addition to quantitative ratings, qualitative suggestions were collected to guide the refinement of the initial prototype before implementation.

Table 6. Results of the expert validation

Validation Aspect	Mathematics Expert	Educational Technology Expert	AI in Education Expert	Mean	Category	Revision Status
Theoretical Foundation	4.70	4.80	4.90	**4.80**	Very Valid	Minor Revision
Learning Syntax	4.80	4.70	4.90	**4.80**	Very Valid	Revised
Social System	4.60	4.70	4.80	**4.70**	Very Valid	Minor Revision
Principles of Reaction	4.70	4.80	4.80	**4.77**	Very Valid	Revised
Support System	4.80	4.90	4.80	**4.83**	Very Valid	No Revision
Instructional & Accompanying Impacts	4.90	4.80	4.90	**4.87**	Very Valid	No Revision
Overall Mean	4.75	4.78	4.85	4.79	Very Valid	Ready for Field Testing

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As shown in Table 6, all dimensions of the SMART-TPACK instructional model obtained very valid ratings from the three expert validators, with an overall mean score of 4.79 out of 5.00. The highest ratings were obtained for the Instructional and Accompanying Impacts (M = 4.87) and Support System (M = 4.83), indicating strong agreement among experts regarding the potential effectiveness and practical feasibility of the model. The Theoretical Foundation and Learning Syntax also achieved high validation scores (M = 4.80), suggesting that the instructional stages were conceptually coherent and systematically organized. Although all validation aspects met the criteria for implementation, the validators provided several constructive suggestions to further improve the clarity and practicality of the instructional model. These recommendations were incorporated into the revised prototype before the implementation stage. The profil of expert validation across all instructional dimensions is illustrated in Figure 6.

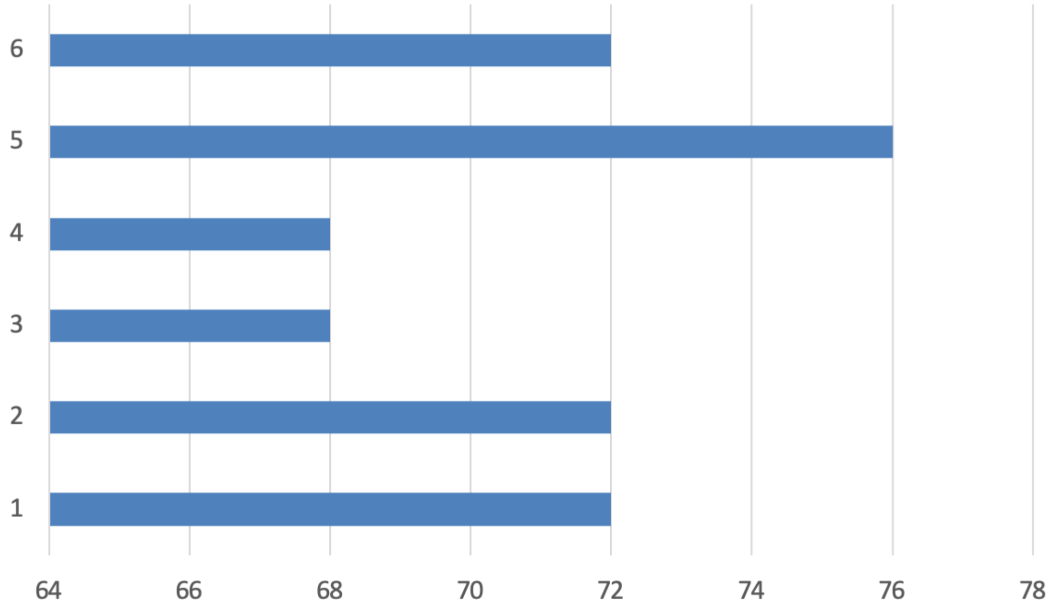

Figure 6. Expert Validation Profile of the SMART-TPACK Instructional Model

Table 7. Summary of Expert Suggestions and Model Revisions

Expert	Major Suggestions	Revisions Implemented
Mathematics Education Expert	Increase opportunities for higher-order mathematical reasoning and authentic problem-solving activities.	Additional problem-solving tasks requiring mathematical reasoning and real-world applications were incorporated into the Construction stage.
Educational Technology Expert	Clarify the integration of AI tools within each instructional stage and strengthen the alignment between technology and pedagogy.	AI-supported learning activities were explicitly embedded into each stage of the SMART-TPACK learning syntax.

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AI in Education Expert	Emphasize responsible AI use, ethical considerations, and verification of AI-generated outputs.	AI ethics, critical evaluation of AI responses, and responsible AI practices were incorporated into the Reflection stage and supporting learning guidelines.

The revisions suggested by the validators primarily focused on enhancing instructional clarity rather than modifying the fundamental structure of the model. Consequently, the core components of the SMART-TPACK instructional model remained unchanged, while its instructional procedures, AI integration, and supporting learning activities were refined to improve usability and pedagogical coherence. Following these revisions, the model was finalized as Prototype II and considered suitable for classroom implementation during the Implementation phase.

Implementation Results

Following the expert validation process and subsequent revisions, the SMART-TPACK instructional model (Prototype II) was implemented in the experimental class to examine its feasibility in an authentic instructional setting. The implementation involved 30 pre-service mathematics teachers enrolled in the Mathematics Education Study Program. A parallel class consisting of 30 students received conventional instruction and served as the control group during the effectiveness evaluation stage.

The implementation followed the four instructional stages of the SMART-TPACK model, namely Exploration, Integration, Construction, and Reflection. During the Exploration stage, students utilized AI-assisted learning resources to investigate mathematical concepts and identify relevant information for problem solving. In the Integration stage, students collaboratively combined technological tools, pedagogical strategies, and mathematical content while designing learning activities supported by Artificial Intelligence. The Construction stage emphasized collaborative problem solving through authentic mathematical tasks, enabling students to construct conceptual understanding and mathematical reasoning. Finally, the Reflection stage encouraged students to evaluate their learning processes, discuss alternative solution strategies, and critically examine AI-generated responses.

Classroom observations conducted throughout the implementation indicated that the instructional procedures could be carried out according to the learning syntax established during the design phase. Students actively participated in AI-assisted exploration, collaborative discussions, and mathematical problem-solving activities. The use of AI was primarily observed as a learning support tool for generating multiple solution strategies, visualizing mathematical concepts, and facilitating reflective discussions under lecturer supervision.

The implementation also demonstrated that the revised instructional syntax was practical and feasible for classroom use. The integration of Artificial Intelligence within each learning stage enabled students to engage with

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mathematical concepts through a more structured and interactive learning process while maintaining the central role of pedagogical guidance provided by the lecturer.

The implementation results indicate that the SMART-TPACK instructional model was successfully implemented in accordance with its intended instructional procedures. The successful implementation of Prototype II provided the basis for evaluating the effectiveness of the instructional model in improving pre-service mathematics teachers' mathematical cognitive competence.

Effectiveness of the SMART-TPACK Instructional Model

Descriptive Statistics

The effectiveness of the SMART-TPACK instructional model was evaluated by comparing students' mathematical cognitive competence before and after the intervention. Descriptive statistics for the pretest and posttest scores of both the experimental and control groups are presented in Table 8.

Table 8. Descriptive Statistics of Pretest and Posttest Scores

Group	N	Pretest Mean ± SD	Posttest Mean ± SD	Mean Gain
Experimental	30	72.00 ± 4.46	84.93 ± 5.43	12.93
Control	30	73.00 ± 3.43	79.20 ± 3.99	6.20

The descriptive results indicate that both groups showed improved mathematical cognitive competence after the instructional intervention. However, the experimental group demonstrated a substantially greater increase than the control group. The mean score of the experimental group increased from 72.00 to 84.93, representing a gain of 12.93 points, whereas the control group improved from 73.00 to 79.20, with a mean gain of 6.20 points. These findings provide preliminary evidence that students who learned using the SMART-TPACK instructional model achieved greater learning improvements than those receiving conventional instruction.

Assumption Testing

Before conducting hypothesis testing, the data were examined for normality and homogeneity. The results are presented in Tables 9 and 10.

Table 9. Shapiro–Wilk Normality Test

Variable	W	p-value	Interpretation
Experimental Pretest	—	< .001	Not Normally Distributed
Experimental Posttest	—	.006	Not Normally Distributed
Control Pretest	—	< .001	Not Normally Distributed
Control Posttest	—	.009	Not Normally Distributed

The Shapiro–Wilk test indicated that several datasets did not meet the normality assumption ($p < .05$). Considering the relatively equal sample size in both groups ($n = 30$) and the robustness of parametric procedures under moderate

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deviations from normality, further analyses were conducted using parametric statistics while the assumption of homogeneity was also examined.

Table 10. Levene's Test of Homogeneity

Variable	Levene Statistic	p-value	Interpretation
Pretest	—	.285	Homogeneous
Posttest	—	.427	Homogeneous

Levene's test confirmed that the variances of the experimental and control groups were homogeneous for both pretest and posttest scores ($p > .05$), indicating that the assumption of homogeneity of variance was satisfied.

Paired-Samples t-Test

To determine whether students' mathematical cognitive competence improved significantly after the implementation of the SMART-TPACK instructional model, paired-samples t-tests were conducted for both groups.

Table 11. Paired-Samples t-Test Results

Group	Mean Difference	T	df	p-value
Experimental	12.93	21.67	29	< .001
Control	6.20	15.09	29	< .001

The paired-samples t-test demonstrated statistically significant improvements in both groups ($p < .001$). However, the experimental group exhibited a considerably larger mean improvement than the control group, indicating that the SMART-TPACK instructional model produced stronger learning gains than conventional instruction.

Independent-Samples t-Test

To compare students' achievement after the instructional intervention, an independent-samples t-test was performed using the posttest scores.

Table 12. Independent-Samples t-Test

Comparison	T	df	p-value
Experimental vs Control (Posttest)	4.66	58	< .001

The independent-samples t-test revealed a statistically significant difference between the posttest scores of the experimental and control groups ($t = 4.66$, $p < .001$). Students who learned using the SMART-TPACK instructional model achieved significantly higher posttest scores than those receiving conventional instruction.

N-Gain Analysis

To evaluate the magnitude of learning improvement, the normalized gain (N-Gain) was calculated for both groups.

Table 13. N-Gain Analysis

Group	Mean N-Gain	Category

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Experimental	0.479	Medium
Control	0.233	Low

The N-Gain analysis indicates that the experimental group achieved a medium level of learning improvement, whereas the control group remained within the low improvement category. These findings suggest that the SMART-TPACK instructional model contributed to a greater enhancement of students' mathematical cognitive competence than conventional learning.

Effect Size

To determine the practical significance of the SMART-TPACK instructional model, Cohen's d effect size was calculated.

Table 14. Effect Size of the SMART-TPACK Instructional Model

Variable	Cohen's d	Interpretation
Mathematical Cognitive Competence	1.92	Very Large Effect

The calculated Cohen's d value of 1.92 indicates a very large practical effect, demonstrating that the SMART-TPACK instructional model substantially improved students' mathematical cognitive competence beyond statistical significance. This finding supports the effectiveness of integrating artificial intelligence with the TPACK framework in mathematics instruction.

Discussion

Why Did the SMART-TPACK Instructional Model Improve Mathematical Cognitive Competence?

The findings of this study indicate that students who participated in the SMART-TPACK instructional model demonstrated greater improvements in mathematical cognitive competence than those who experienced conventional instruction. Rather than attributing these improvements solely to the use of artificial intelligence (AI), the results suggest that the effectiveness of SMART-TPACK lies in the systematic integration of AI technologies with technological, pedagogical, and content knowledge within a coherent instructional framework. This integration created learning experiences that actively engaged prospective mathematics teachers in exploring, applying, and reflecting on mathematical concepts through technology-supported inquiry, thereby facilitating deeper conceptual understanding and more meaningful learning experiences (Castrillón-Yepes et al., 2020; Sulistyorini & Yazidah, 2025; Wulandari et al., 2025)

Unlike conventional mathematics instruction, which often emphasizes procedural knowledge and teacher-centered explanations, the SMART-TPACK instructional model encourages students to interact with AI-based learning tools throughout each phase of learning. During the exploration stage, AI applications supported students in visualizing mathematical concepts, generating multiple solution strategies, and providing immediate feedback on problem-solving processes. These features allowed students to receive personalized learning

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support while simultaneously strengthening their conceptual understanding and metacognitive awareness. Such learning environments are consistent with constructivist perspectives, which argue that meaningful learning occurs when learners actively construct knowledge through interaction, reflection, and authentic problem-solving experiences (Conrad, 2022; Miller-First et al., 2017).

The integration of AI within the TPACK framework also strengthened the pedagogical role of technology rather than positioning technology as an instructional objective. Previous studies have emphasized that technology alone does not improve learning outcomes unless it is effectively integrated with pedagogy and disciplinary content (Alvero, 2025; Dewi et al., 2025; Navasca, 2025) In the SMART-TPACK model, AI functioned as an instructional partner that supported mathematical reasoning, adaptive feedback, and collaborative knowledge construction. Consequently, technology became a cognitive scaffold that assisted students in understanding complex mathematical ideas instead of merely serving as a presentation medium. This finding supports recent research suggesting that generative AI has considerable potential to enhance higher-order thinking and problem-solving when embedded within sound pedagogical designs (Alshamsi, 2025; Karimian et al., 2025; Xiong & Zhang, 2026).

Another factor contributing to the effectiveness of SMART-TPACK is its structured learning syntax developed through the ADDIE model. The sequential stages of analysis, guided exploration, collaborative knowledge construction, implementation, and reflective evaluation ensured that learning activities progressed systematically from conceptual understanding toward independent application. Such instructional sequencing is particularly important in mathematics education because conceptual understanding develops gradually through iterative cycles of exploration, practice, feedback, and reflection. The reflective component of SMART-TPACK further encouraged prospective teachers to evaluate both their mathematical reasoning and their pedagogical decisions when utilizing AI-supported technologies, thereby promoting self-regulated learning and professional competence (Elifas & Simuja, 2024; School of Chemical and Process Engineering, University of Leeds, Leeds LS2 9JT & Ravi, 2025)

These findings suggest that the effectiveness of SMART-TPACK should not be interpreted simply as the result of introducing artificial intelligence into mathematics classrooms. Instead, its effectiveness emerges from the coherent integration of AI, pedagogical strategies, mathematical content, and reflective instructional practices within a unified instructional model. This integrated design enables prospective mathematics teachers not only to improve their mathematical cognitive competence but also to develop the technological and pedagogical capacities required to teach mathematics effectively in AI-supported learning environments.

These findings further indicate that the instructional value of SMART-TPACK extends beyond improving students' cognitive achievement. Its primary contribution lies in demonstrating how artificial intelligence can be pedagogically integrated within the TPACK framework to support mathematics teacher education. This broader contribution is discussed in the following section.

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Contribution of AI Integration within the TPACK Framework

The present study extends the existing TPACK framework by demonstrating how artificial intelligence can be systematically integrated into mathematics teacher education through a structured instructional model. While the original TPACK framework emphasizes the dynamic interaction among technological knowledge, pedagogical knowledge, and content knowledge (Elifas & Simuja, 2024; Xiong & Zhang, 2026), the rapid advancement of artificial intelligence has introduced new instructional possibilities that require a broader interpretation of technological competence. In contemporary educational contexts, teachers are expected not only to operate digital technologies but also to critically select, evaluate, and integrate AI-based tools that support learning, assessment, and instructional decision-making (Karimian et al., 2025; Zhang & Zhou, 2023).

Unlike many previous studies that have investigated AI applications as isolated educational technologies, the SMART-TPACK instructional model positions artificial intelligence as an integral component of instructional design rather than as a standalone technological tool. AI was incorporated throughout the learning process to facilitate concept exploration, provide adaptive feedback, support mathematical reasoning, and encourage reflective learning. Consequently, AI functioned as a cognitive partner that enhanced students' engagement with mathematical concepts while simultaneously strengthening the interaction between technology, pedagogy, and content knowledge. This finding supports recent arguments that the educational value of AI depends not on the technology itself but on how it is pedagogically designed and implemented within meaningful learning environments (Oláh & Šimek, 2025; Xiong & Zhang, 2026)

The findings also contribute to the growing body of literature advocating the integration of AI literacy into teacher education. Recent international reports have emphasized that future teachers require competencies extending beyond conventional digital literacy to include the ability to understand AI capabilities, recognize its limitations, evaluate AI-generated information critically, and employ AI responsibly in educational settings. The SMART-TPACK instructional model addresses these expectations by embedding AI-supported inquiry, collaborative problem-solving, and reflective practice within mathematics instruction. Through these learning experiences, prospective teachers develop not only mathematical competence but also the professional skills required to integrate AI ethically and effectively into future classroom practice.

Compared with previous instructional models that primarily focused on technology-enhanced learning or digital pedagogy, SMART-TPACK offers a more comprehensive instructional framework by explicitly combining AI-assisted learning activities with the pedagogical principles of TPACK. Rather than treating AI as an additional technological resource, the model organizes AI integration into a coherent sequence of learning activities developed through the ADDIE framework. This systematic organization enables prospective mathematics teachers to experience how AI can support conceptual understanding,

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instructional planning, classroom interaction, and reflective evaluation within a unified pedagogical process.

From a theoretical perspective, this study suggests that the TPACK framework remains highly relevant for contemporary teacher education but requires continuous adaptation to accommodate emerging educational technologies. The SMART-TPACK instructional model therefore should not be viewed as replacing TPACK; instead, it operationalizes and extends the framework by demonstrating how AI can be meaningfully integrated into pedagogical practice. In this respect, the model contributes to the ongoing evolution of technology integration theory and provides empirical evidence that AI-supported instructional design can strengthen the development of professional competencies among prospective mathematics teachers.

Comparison with Previous Studies

The findings of this study are generally consistent with previous research demonstrating that technology-integrated instructional approaches can enhance students' learning outcomes when supported by appropriate pedagogical strategies. Numerous studies have reported that the TPACK framework enables teachers to integrate technology, pedagogy, and subject matter more effectively, thereby improving students' conceptual understanding and classroom engagement (Deb & Pradhan, 2023; Souza & Cardoso, 2024). Similarly, recent investigations have shown that artificial intelligence can facilitate personalized learning, provide adaptive feedback, and improve students' higher-order thinking skills when embedded within well-designed instructional environments (Alshamsi, 2025; Alvero, 2025). The present findings reinforce these conclusions by demonstrating that the integration of AI within a structured pedagogical framework can positively support mathematics learning among prospective teachers.

However, the present study extends previous research in several important ways. Most earlier studies examined either the implementation of the TPACK framework without explicitly incorporating artificial intelligence or investigated AI applications primarily as instructional tools rather than as components of a comprehensive instructional model (Pasmala et al., 2025). Consequently, previous findings often emphasized technological adoption or students' perceptions of AI, while providing limited guidance regarding how AI should be systematically embedded within the instructional process. In contrast, the SMART-TPACK instructional model developed in this study integrates AI throughout the learning sequence, beginning with concept exploration, continuing through collaborative knowledge construction, and concluding with reflective evaluation. This structured integration provides a clearer pedagogical pathway for prospective mathematics teachers to employ AI meaningfully in classroom practice.

The present findings also contribute to mathematics teacher education research by addressing an increasingly important issue: preparing future teachers for AI-supported educational environments. International organizations have highlighted the necessity of equipping teachers with competencies that combine

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technological expertise, pedagogical knowledge, ethical awareness, and critical evaluation of AI-generated information. While previous studies have primarily focused on improving digital competence, the SMART-TPACK model expands this perspective by explicitly integrating AI literacy into mathematics instruction. As a result, prospective teachers are encouraged not only to use AI technologies but also to critically evaluate AI-generated solutions, compare alternative mathematical reasoning, and make pedagogically informed instructional decisions.

Another noteworthy finding is that the effectiveness of SMART-TPACK appears to arise from the interaction among its instructional components rather than from the presence of AI alone. This observation aligns with contemporary educational theories emphasizing that learning outcomes are influenced more by instructional design than by technology itself (Cunha et al., 2024; Veletsianos, 2014). In the present study, AI served as a cognitive support tool within a carefully sequenced instructional process grounded in the TPACK framework and developed through the ADDIE model. This suggests that successful AI integration in education depends on coherent pedagogical planning, structured learning activities, and opportunities for reflection, rather than on technological innovation in isolation.

The comparison with previous studies indicates that the SMART-TPACK instructional model contributes beyond confirming existing evidence regarding technology integration in education. Instead, it offers an empirically validated instructional framework demonstrating how artificial intelligence can be systematically integrated within TPACK to strengthen mathematics teacher preparation. This contribution addresses an important gap identified in previous literature and provides practical guidance for teacher education institutions seeking to incorporate AI into mathematics instruction in a pedagogically meaningful manner.

Practical Implications

The findings of this study have several important implications for mathematics teacher education and the broader implementation of artificial intelligence in educational practice. First, the SMART-TPACK instructional model provides a practical framework for integrating AI into mathematics learning in ways that are pedagogically meaningful rather than technology-driven. As educational institutions increasingly adopt AI-based technologies, teacher preparation programs require instructional models that enable prospective teachers to develop not only technical proficiency but also the pedagogical competence needed to select, adapt, and critically evaluate AI tools for classroom instruction. The SMART-TPACK model offers a structured approach to achieving these objectives by embedding AI within coherent learning activities that promote conceptual understanding, collaborative inquiry, and reflective practice.

Second, the model has important implications for curriculum development in teacher education institutions. Many teacher education curricula currently introduce digital technologies as separate competencies or isolated training

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sessions, resulting in fragmented technology integration. The SMART-TPACK instructional model demonstrates that AI competencies can be incorporated across instructional planning, classroom implementation, assessment, and reflective evaluation within a unified pedagogical framework. Such integration supports the development of future mathematics teachers who are capable of designing learning experiences that respond to the rapidly evolving demands of Education 5.0 and AI-supported learning environments.

Third, the study contributes to the professional development of in-service mathematics teachers. As generative AI tools become increasingly accessible, many teachers continue to experience uncertainty regarding their pedagogical use, ethical implications, and instructional value. The structured syntax of SMART-TPACK provides practical guidance for integrating AI responsibly into mathematics instruction while maintaining teachers' central role in facilitating learning. Rather than replacing teachers' professional judgment, AI functions as a cognitive support tool that enhances lesson preparation, classroom interaction, feedback, and students' mathematical reasoning.

The findings also have implications for educational policymakers and curriculum developers. National initiatives promoting digital transformation in education increasingly emphasize artificial intelligence as a strategic priority. However, successful implementation depends not only on technological infrastructure but also on the availability of evidence-based instructional models that demonstrate how AI can be effectively integrated into classroom practice. The SMART-TPACK instructional model offers one such evidence-informed framework that may support policy initiatives aimed at strengthening digital innovation, teacher competence, and mathematics education in higher education institutions. Although this study was conducted within mathematics teacher education, the pedagogical principles underlying SMART-TPACK are sufficiently flexible to be adapted to other disciplines that require technology-enhanced problem solving and critical thinking. Consequently, the model has the potential to support interdisciplinary learning and may serve as a reference for future instructional innovation across diverse educational contexts.

Theoretical Contributions

The present study makes several important theoretical contributions to the literature on technology integration, artificial intelligence, and mathematics teacher education. First, this study extends the application of the Technological Pedagogical Content Knowledge (TPACK) framework by demonstrating how artificial intelligence can be systematically incorporated into an instructional model developed specifically for prospective mathematics teachers. While the original TPACK framework conceptualizes the interaction among technology, pedagogy, and content knowledge (Alshamsi, 2025; Sulistyorini & Yazidah, 2025), it was developed before the rapid emergence of generative artificial intelligence. Consequently, the framework provides limited guidance regarding how AI can be pedagogically integrated into classroom instruction. The SMART-TPACK instructional model addresses this limitation by operationalizing AI integration

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within a structured sequence of learning activities, thereby expanding the practical application of the TPACK framework in contemporary educational settings.

Second, this study contributes to the growing field of AI-supported learning by demonstrating that the effectiveness of artificial intelligence depends on its pedagogical integration rather than on the technology itself. Existing studies have frequently focused on evaluating the capabilities of AI tools or investigating students' perceptions of AI-assisted learning. In contrast, the present study proposes that AI should function as a pedagogically embedded cognitive support system that facilitates concept exploration, adaptive feedback, collaborative problem-solving, and reflective learning. This perspective shifts the emphasis from technology adoption toward instructional design, reinforcing the view that meaningful learning outcomes are achieved when emerging technologies are integrated within coherent pedagogical frameworks.

Third, the study contributes to instructional design research by integrating the ADDIE development model with the TPACK framework and AI-supported learning. Rather than treating instructional design and technology integration as separate processes, SMART-TPACK demonstrates how systematic instructional development can guide the meaningful incorporation of AI into mathematics education. This integration strengthens the theoretical relationship between instructional design principles and technology integration theory, providing a replicable framework for future model development in other educational disciplines.

Another important contribution lies in the empirical validation of the SMART-TPACK instructional model. Many conceptual discussions on AI in education remain theoretical and provide limited empirical evidence regarding instructional implementation. By employing a research and development approach that included needs analysis, expert validation, classroom implementation, and effectiveness evaluation, this study provides empirical support for the practical applicability of AI-integrated instructional models in teacher education. The findings therefore contribute not only to theoretical discussions but also to evidence-based instructional innovation.

This study suggests that future developments of the TPACK framework should move beyond viewing technology as a general digital resource and instead recognize artificial intelligence as a transformative educational technology that requires new pedagogical competencies. Accordingly, the SMART-TPACK instructional model represents a theoretical extension of TPACK by illustrating how AI can be systematically integrated into instructional design while preserving the balanced interaction among technological, pedagogical, and content knowledge. This contribution offers a conceptual foundation for future research examining AI-enhanced teacher education and instructional innovation in the digital era.

Limitations and Future Research

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Although this study provides empirical evidence supporting the effectiveness of the SMART-TPACK instructional model, several limitations should be acknowledged. First, the implementation phase involved prospective mathematics teachers from a single teacher education institution, which may limit the generalizability of the findings to other educational contexts. Differences in institutional characteristics, technological infrastructure, and students' prior experience with artificial intelligence may influence the implementation and effectiveness of the instructional model. Therefore, caution should be exercised when generalizing these findings to broader populations.

Second, the effectiveness evaluation primarily focused on students' mathematical cognitive competence following a relatively short instructional intervention. While the results indicate positive learning outcomes, the study did not investigate the long-term retention of mathematical knowledge or the sustained development of AI-related pedagogical competencies. Longitudinal studies are therefore needed to determine whether the observed improvements can be maintained over extended periods of instructional practice.

Another limitation concerns the scope of learning outcomes examined in this study. The evaluation emphasized cognitive achievement, whereas other important competencies required for future mathematics teachers—such as critical thinking, creative problem-solving, AI literacy, collaborative skills, self-regulated learning, and ethical decision-making in the use of artificial intelligence—were not directly assessed. Future research should incorporate these multidimensional competencies to provide a more comprehensive evaluation of AI-supported instructional models.

Future studies are also encouraged to validate and implement the SMART-TPACK instructional model across different educational levels, subject areas, and cultural contexts. Comparative studies involving multiple universities or schools would provide stronger evidence regarding the model's adaptability and external validity. In addition, future researchers may explore the integration of emerging generative AI technologies, learning analytics, and intelligent tutoring systems to further refine the SMART-TPACK model and expand its applicability in mathematics education and other disciplines.

Overall, despite these limitations, the present study provides an important foundation for future investigations into AI-supported instructional design. The findings demonstrate that the systematic integration of artificial intelligence within the TPACK framework through an ADDIE-based development process represents a promising direction for preparing future mathematics teachers to meet the challenges of digital transformation in education.

CONCLUSION

This study demonstrates that preparing prospective mathematics teachers for the era of artificial intelligence requires more than simply introducing emerging technologies into classroom practice. Instead, effective AI integration depends on the availability of pedagogically grounded instructional models that systematically connect technological capabilities with pedagogical strategies and

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mathematical content knowledge. Through a research and development approach based on the ADDIE model, this study developed and empirically validated the SMART-TPACK instructional model as a structured framework for AI-supported mathematics teacher education. The overall findings indicate that the model is theoretically sound, practically feasible, and effective in supporting the development of students' mathematical cognitive competence.

Beyond its empirical findings, this study contributes to the advancement of educational theory by extending the practical application of the TPACK framework within the context of artificial intelligence. Rather than conceptualizing AI merely as an instructional technology, SMART-TPACK positions AI as a pedagogically embedded cognitive partner that supports exploration, reasoning, collaborative knowledge construction, and reflective learning. Consequently, the study provides an operational model illustrating how AI can be systematically integrated into instructional design while preserving the balanced interaction among technological, pedagogical, and content knowledge. This contribution responds to the growing need for theoretical frameworks capable of addressing the educational challenges emerging in the age of generative artificial intelligence.

The study also offers important practical and policy implications. For teacher education institutions, SMART-TPACK provides an evidence-based instructional framework for preparing future mathematics teachers to integrate AI responsibly and effectively into classroom practice. For teacher educators and curriculum developers, the model offers practical guidance for embedding AI competencies within mathematics education rather than treating them as isolated technological skills. At the policy level, the findings support ongoing initiatives promoting digital transformation in education by demonstrating that successful AI implementation requires pedagogically validated instructional models alongside technological infrastructure and institutional support.

Several limitations should be acknowledged. The implementation of the SMART-TPACK model was conducted within a single teacher education institution and focused primarily on students' mathematical cognitive competence during a relatively short intervention period. Accordingly, future research should examine the model across diverse educational settings, larger and more heterogeneous participant populations, and longer implementation periods. Further investigations are also encouraged to explore the influence of SMART-TPACK on broader educational outcomes, including AI literacy, critical thinking, creativity, self-regulated learning, professional teaching competence, and ethical decision-making in AI-supported learning environments.

This study contributes to the international discourse on artificial intelligence in teacher education by providing an empirically validated instructional model that bridges instructional design, TPACK, and AI-supported pedagogy. As educational systems worldwide continue to respond to rapid technological transformation, the SMART-TPACK instructional model offers a theoretically grounded and practically applicable framework for preparing future mathematics teachers capable of teaching effectively and responsibly in AI-enhanced learning environments.

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Author Contributions

M. Nurhadi: Conceptualization, Methodology, Data Collection, Data Analysis, Investigation, and Writing – Original Draft.
D. Iskandar: Conceptualization, Methodology, Data Collection, Data Analysis, Investigation, and Writing – Review & Editing.

All authors have read and approved the final version of the manuscript.

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Ethics Statement

This study involved human participants, namely pre-service mathematics teachers at Universitas Pasundan. Prior to data collection, research permission was obtained from the Faculty of Teacher Training and Education and the Mathematics Education Study Program, Universitas Pasundan. All participants were informed about the objectives, procedures, and voluntary nature of the study, and written informed consent was obtained before participation. Participants' identities were kept confidential, and the data were analyzed and reported in an anonymized and aggregated form. The study was conducted in accordance with the institutional regulations governing educational research at Universitas Pasundan.

Conflict of Interest

The authors declare that they have no financial, professional, or personal conflicts of interest that could have influenced the conduct of the research, the analysis of the data, or the preparation of this manuscript.

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