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A TPACK-Based Framework for Integrating Robotics and AI in STEM Education: Development and Validation through Mixed Methods

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ABSTRACT

The rapid advancement of robotics and artificial intelligence (AI) has reshaped the educational landscape, particularly within Science, Technology, Engineering, and Mathematics (STEM) disciplines. While these technologies hold promise for enhancing computational thinking, problem-solving, creativity, and collaboration, their integration in classrooms has often remained fragmented due to limited teacher preparedness, resource constraints, and inadequate pedagogical frameworks. This study developed and validated a Technological Pedagogical Content Knowledge (TPACK)-based framework to guide the effective incorporation of robotics and AI in STEM education. A mixed-methods exploratory sequential design was employed, combining qualitative data from interviews and classroom observations with quantitative insights from large-scale teacher surveys and student assessments. The framework was empirically tested to evaluate its impact on both teaching practices and student learning outcomes. Findings provided a comprehensive understanding of teachers' TPACK levels, established a validated integration framework, and generated actionable recommendations for professional development and policy. The study advanced theoretical discourse on TPACK in the digital era while offering practical guidance for educators and policymakers to promote meaningful adoption of robotics and AI in STEM classrooms.

Keywords: *Robotics, Artificial Intelligence (AI), STEM Education, TPACK Framework, Teacher Preparedness, Educational Technology Integration*

INTRODUCTION

The 21st century has seen technological progress like never before, and it has changed every field, including education. Robotics and artificial intelligence (AI) are two of the most important new technologies that are being used more in Science, Technology, Engineering, and Mathematics (STEM) education. These technologies opened new ways to teach and learn by helping people develop higher-order skills like creativity, problem-solving, computational thinking, collaboration, and adaptability (Xu & Ouyang, 2022). Robotics, as a hands-on tool, let students design, build, and program mechanical systems that were like how things work in the real world. This got them involved in solving real-world problems. AI-driven adaptive learning platforms, intelligent tutoring systems, and data-driven assessment tools that tailored learning experiences and offered customised feedback to students (Fitriyah, Sutadji, Dewi, & Kusumaningrum, 2024; Saharuddin, Nasir, & Mahmud, 2025). These technologies worked together to get students more interested in learning and give them the skills they need for the digital economy.

Even though it had a lot of potential, the use of robotics and AI in STEM education was still not very organised. This was because there weren't enough good teaching frameworks, teachers weren't ready, and the use of technology didn't always match up with the goals of the curriculum. Many teachers didn't have the professional knowledge they needed to use robotics and AI well because their training and professional development focused more on subject matter and general teaching methods than on new digital technologies (Nindiasari, Restiana, & Pamungkas, 2021). Teachers had a hard time making lesson plans that used robotics kits or AI platforms in a way that made sense with the rest of the curriculum, even when they were available. For example, robotics could help students learn more about engineering design, physics, or coding. However, if it wasn't used in a way that fit with the overall learning goals, it was often only used for extracurricular activities or small projects that weren't connected to the bigger picture (Brender, El-Hamamsy, Bruno, Chessel-Lazzarotto, Dehler Zufferey, & Mondada, 2021). AI tools also gave students personalised paths, but teachers often didn't know how to use AI-generated insights to help students learn in the best way possible. This gap between the availability of tools and their meaningful use in teaching showed how important it was to have structured frameworks to help with integration.

Mishra and Koehler (2006) came up with the Technological Pedagogical Content Knowledge (TPACK) framework, which was a good way to deal with this problem. TPACK focused on the overlap of three types of teacher knowledge: Content Knowledge (CK), Pedagogical Knowledge (PK), and Technological Knowledge (TK). Not only did teachers need to know about each subject, but they also needed to be able to combine them in a way that worked for each learning situation. In STEM education (Faisal, et al., 2023), TPACK helped teachers connect technology with subject matter and teaching methods when it came to robotics and AI. For instance, robotics could be employed to impart mathematical concepts via measurement and programming tasks, whereas AI-driven platforms facilitated scientific problem-solving (Fitriyah et al., 2024). In this way, TPACK encouraged purposeful integration, which went beyond just using technology to make teaching better and learning outcomes better.

Still, there were still problems. Teachers said there weren't enough training opportunities and institutional support for trying out robotics and AI (Saharuddin et al., 2025). Infrastructure problems, like the high cost of robotics kits, slow internet connections, and lack of technical support, made it even harder to use robotics, especially in schools with few resources (Ismail, Zubair, Alqadri, & Basariah, 2023). Also, the fast pace of technological change made it hard for teachers to keep up with new skills, which left many unprepared or overwhelmed. As a result, even though students learnt about robotics or AI, their learning experiences were often broken up, inconsistent, and not in line with what they were supposed to learn. This kind of misalignment could turn transformative technologies into superficial extras instead of the main tools for educational innovation (Xu & Ouyang, 2022; Faisal, et al., 2023).

Empirical studies elucidated both opportunities and deficiencies. Xu and Ouyang (2022), in a systematic review of 63 empirical studies on AI in STEM education from 2011 to 2021, noted significant disparities in integration depth, quality, and learning outcomes. Nindiasari et al. (2021) assessed TPACK levels among mathematics lecturers, revealing robust pedagogical foundations yet deficiencies in technological knowledge and its integration with pedagogy. In the same way, Yanış and Yürük (2020) created and tested an educational robotics TPACK self-efficacy scale (ER-TPACK) for pre-service science teachers. This shows how important it is to measure how ready teachers are to use technology in the classroom.

Teacher professional development became a key factor. Good training didn't just teach technical skills; it also taught teachers how to use robotics and AI in STEM lessons. For instance, teachers who are trained in project-based learning could help students work together to design robots that solve real-world problems. This would connect engineering principles with creativity and teamwork. AI-powered platforms could also help with differentiated instruction, giving advanced students more of a challenge while giving struggling students the help they need. These methods gave teachers the power to see robotics and AI as more than just cool new things; they were also important tools that fit with the curriculum and helped students learn (Fitriyah et al., 2024).

Another important part was making clear, flexible teaching frameworks. Structured frameworks based on TPACK helped teachers choose the right technologies, connect them to the subject matter, and come up with plans that got students involved and helped them learn the most. For example, robotics could be used in lower secondary math classes to teach geometry and measurement, and advanced robotics and AI could be used in upper secondary computer science or engineering classes (Yanış & Yürük, 2020). AI tools could also be connected to learning goals, like encouraging students to ask questions in science or helping them with group writing projects by using natural language processing. These structured frameworks made things less uncertain for teachers and made sure that technology was used the same way in all classrooms.

Research also emphasised the necessity of empirically assessing the influence of robotics and AI on student learning outcomes. Although evidence indicated enhancements in computational thinking and engagement, there exists a paucity of studies evaluating the long-term impacts on critical thinking, creativity, or collaboration. Mixed-methods research designs integrating surveys, interviews, classroom observations, and pre-/post-test assessments provided significant insights into both opportunities and challenges (Saharuddin et al., 2025). This type of evidence helped teachers do their jobs better and helped policymakers decide how to spend money and what to teach. For example, when AI platforms showed big improvements in personalised learning outcomes, they made a case for investing in AI-based solutions at the system level.

In the end, the use of robotics and AI in STEM education was in line with bigger trends in 21st-century learning, where students were expected to learn skills for industries that change quickly and are driven by technology (Faisal, et al., 2023). Robotics got students interested in design, programming, and systems thinking. It also helped them learn how to work together and communicate through group projects. AI enabled customised learning pathways that adjusted to students' strengths and weaknesses, promoting independence and resilience (Xu & Ouyang, 2022). However, these chances weren't used enough because teachers didn't get enough help. Teachers were very important as people who helped students learn, figured out how well they were doing, and made classrooms that were useful for learning. So, giving teachers the tools they needed to be successful with robotics and AI in the classroom was very important. This included professional development, pedagogical frameworks, and support from the school.

To tackle these challenges, this study created and validated a TPACK-based framework for incorporating robotics and AI into STEM education (Faisal, et al., 2024). The study employed a mixed-methods exploratory sequential design, integrating qualitative data from interviews and classroom observations with quantitative findings from extensive teacher surveys and student assessments. The framework underwent empirical testing to assess its influence on pedagogical methods and student performance. The findings provided a thorough comprehension of teachers' TPACK levels, a validated integration framework, and pragmatic recommendations for professional development and policy. This study enhanced theoretical discussions regarding TPACK in the digital age while offering practical recommendations for educators and policymakers to facilitate the effective integration of robotics and AI in STEM classrooms.

Problem Statement

People were starting to see robotics and AI as important parts of 21st-century education, but they were still not being used consistently or deeply in STEM classrooms. Teachers faced numerous challenges, such as inadequate professional expertise in robotics and AI applications, absence of organised pedagogical frameworks to facilitate integration, resource limitations, and insufficient training opportunities. Also, these technologies were often not used in ways that helped students meet their curriculum goals.

Prior research on robotics and AI in education primarily focused on student outcomes, including enhancements in computational thinking or problem-solving, while neglecting the pedagogical principles essential for enduring classroom practices. Integration efforts often resulted in disjointed or ineffective learning experiences.

This study filled the gap by creating and using a structured, TPACK-based framework that helped teachers systematically and meaningfully include robotics and AI in STEM lessons.

Research Objectives

The primary objective of this study is to create and validate a TPACK-based framework for the integration of robotics and AI into STEM education. The specific goals are:

1. To investigate teachers' current knowledge, attitudes, and practices regarding robotics and AI integration in STEM education.
2. To identify key challenges and opportunities associated with incorporating robotics and AI in classrooms.
3. To design a TPACK-based framework that aligns robotics and AI technologies with STEM content and pedagogy.
4. To evaluate the effectiveness of the proposed framework through empirical evidence from teachers and students.
5. To provide recommendations for professional development programs and policy-level interventions.

Research Questions

1. What is the current state of teachers' TPACK knowledge regarding robotics and AI in STEM education?
2. What barriers and enablers influence the integration of robotics and AI in classrooms?
3. How can a TPACK-based framework be designed to guide effective integration of robotics and AI in STEM teaching?
4. How does the implementation of the framework impact student learning outcomes and teacher practices?

LITERATURE REVIEW

Robotics had become an important part of STEM (Science, Technology, Engineering, and Mathematics) education, giving students chances to learn by doing, solve problems through experience, and work together as a team, all of which are important for success in the 21st century. Robotics made abstract ideas real by letting students design, build, and program machines that did real-world tasks (Faisal, et al., 2023). This was different from traditional classroom instruction, which often focused on theoretical knowledge and rote memorisation. This active involvement not only enhanced students' conceptual comprehension but also fostered their curiosity, creativity, and drive to investigate intricate concepts. Students faced problems that needed logical reasoning, repeated testing, and creative solutions when they built and programmed robots. These are skills that can be used outside of the classroom. Also, robotics encouraged teamwork by requiring people to work together, talk to each other, and share tasks, which is how professional engineering and technology workplaces work. Robotics combined technical knowledge with hands-on experience, closing the gap between theory and practice. This made learning environments richer and helped students develop skills in computational thinking and engineering design (Eguchi, 2019). These skills were especially important for getting students ready for jobs in STEM fields, where it was important to be able to use knowledge creatively and work together.

Artificial Intelligence (AI) applications changed STEM education by making learning more personalised and adaptable, just like robotics. AI-powered systems, such as adaptive learning platforms and smart tutoring tools, looked at student performance data in real time to find out what each student was good at, what they needed to work on, and how they learnt best (Makhdum, et al., 2023). This made it possible for teachers to give each student personalised instruction based on their needs, pace, and learning style. This made the classroom more welcoming and helped close the gap in learning outcomes. For instance, AI-based platforms gave students who were having trouble with certain math concepts extra help and targeted exercises, while also giving advanced learners more difficult tasks to work on. This level of personalisation improved students' grades and helped them think about their own learning processes and strategies. AI also helped higher-order cognitive skills by promoting learning through questions, critical thinking, and self-reflection. Intelligent tutoring systems asked students difficult questions, gave them hints instead of direct answers, and helped them learn how to solve problems on their own. This led to deeper understanding and long-term memory (Luckin et al., 2016; Fitriyah, Sutadji, Dewi, & Kusumaningrum, 2024).

The incorporation of robotics and AI into STEM education was not solely intended to improve technical skills; it also fostered a wider range of competencies suited to the requirements of the digital age (Makhdum, et al., 2023). Robotics got students to think about design, which helped them learn how to empathise with problems, come up with creative solutions, build prototypes, and improve them through testing and feedback. This iterative method was like how engineers work in the real world and helped students develop the skills they need for lifelong learning, such as resilience, adaptability, and perseverance. AI systems also encouraged people and machines to work together, showing students how to use technology as a cognitive partner instead of just a tool (Faisal, et al., 2023). By using AI, students learnt how to use technology, be aware of ethics, and think critically, which helped them deal with the growingly complicated relationship between people and smart systems (Makhdum & Mian, 2012). Robotics and AI both played a role in the development of 21st-century skills like creativity, communication, critical thinking, and collaboration. These skills are widely seen as necessary for success in school, work, and society (Xu & Ouyang, 2022).

Robotics and AI also gave teachers the chance to rethink how they teach and make learning spaces that were more focused on the students, their questions, and their goals. Project-based learning and robotics went well together. In project-based learning, students worked together to design robots that could solve real problems, like automating household chores or making devices that help people with disabilities. These projects combined different STEM fields, so students had to use their scientific knowledge, math skills, engineering design skills, and programming skills all at once. AI made these methods even better by giving teachers data-driven information about how well their students were doing, which helped them make smart decisions about how to teach (Makhdum & Mian, 2012). Using AI-powered analytics, teachers found common mistakes, kept track of students' progress, and changed how they taught to help all kinds of students. This made teaching more effective and gave teachers more time to mentor, lead discussions, and help students grow socially and emotionally. In this way, AI helped human teachers instead of replacing them, making it easier for them to give personalised, high-quality education (Saharuddin, Nasir, & Mahmud, 2025).

Even with these benefits, using robotics and AI in STEM education was hard, which kept them from reaching their full potential (Faisal, et al., 2024). Teachers often had problems like not enough training, not being sure how to use technology, not having enough resources, and not having the right tools for the standards set by the curriculum. Without enough help, teachers often used robotics and AI in a shallow way, as separate parts of teaching and learning instead of as important parts (Angeli & Valanides, 2020). Ethical issues related to AI, such as data privacy, algorithmic bias, and the risk of becoming too dependent on technology, needed to be carefully thought out to make sure that everyone had a fair chance, that everything was clear, and that everyone was included (Abbas & Faisal, et al., 2024). Likewise, robotics programs must be available to all students, irrespective of socioeconomic status, to avert the exacerbation of the digital divide (Ismail, Zubair, Alqadri, & Basariah, 2023).

The Technological Pedagogical Content Knowledge (TPACK) framework marked a substantial progression in educational theory by augmenting Shulman's Pedagogical Content Knowledge (PCK) model to incorporate technology as an essential domain. Shulman's PCK stressed the importance of understanding how pedagogy and content work together to help teachers teach well. TPACK, on the other hand, made it clear that teachers need to know how to use technology (TK) along with pedagogical knowledge (PK) and content knowledge (CK) in today's classrooms (Mishra & Koehler, 2006). The framework stressed how these three areas were always changing and connected, and how they didn't work on their own but instead interacted with each other in complicated ways. For example, a teacher might know a lot about math (CK) and have good ways to teach (PK), but they might not know how to use technology to show things like measurement, geometry, or problem-solving (Abbas & Faisal, et al., 2024). Likewise, educators skilled in programming and robotics (TK) may find it challenging to integrate these tools effectively with scientific or engineering curricula without suitable pedagogical strategies. The TPACK framework underscored that effective technology integration necessitated educators to seamlessly amalgamate knowledge domains to create impactful, contextually pertinent, and student-centered learning experiences (Schmidt et al., 2009; Fitriyah et al., 2024).

When used to look at how robotics and AI can be used together in STEM education, TPACK gave us a strong way to understand how these technologies worked with subject matter and changed how we teach. From a content standpoint, robotics and AI represented fundamental disciplinary concepts: robotics involved students in engineering design, physics, mathematics, and computer science, whereas AI introduced principles of data analysis, algorithms, and machine learning. Teachers needed to understand both the subject matter and how these technologies could make abstract ideas tangible. For instance, a robotics project that had students build a robot that could get through a maze helped them learn math and engineering. In the same way, an AI-powered adaptive platform in a science classroom helped with differentiated instruction by matching practice questions to each student's knowledge gaps (Yanış & Yürük, 2020).

Integrating robotics and AI into teaching meant changing how teachers taught so that they could use technology to help students reach their learning goals (Abbas & Faisal, et al., 2024). Conventional teacher-centered approaches frequently constrained the capabilities of robotics and AI, which flourished in inquiry-driven, collaborative, and exploratory settings. Robotics was best taught through project-based learning, inquiry-driven instruction, and working together to solve problems. AI, on the other hand, needed teaching methods that included scaffolding, adaptive feedback, and activities that made students think about what they had learnt. Teachers had to change and add to their teaching methods to fit the interactive and student-centered nature of these tools. This required both technical skill and creative teaching (Angeli & Valanides, 2020; Brender et al., 2021).

For meaningful integration, it was important for teachers to be confident and skilled in using robotics and AI. Many teachers didn't have enough training, experience, or understanding of how to use these tools in their classes. TPACK highlighted the importance of developing robust technological knowledge and understanding how these technologies interacted with pedagogy and content. Professional development programs based on TPACK principles offered hands-on training, showed how to use different teaching methods, and showed how to meet curriculum standards. These types of programs helped teachers gain technical confidence and pedagogical insight, which made it easier for them to incorporate robotics and AI into their lessons in a meaningful way (Nindiasari, Restiana, & Pamungkas, 2021).

Mixed-methods research provided a thorough framework for investigating intricate educational phenomena such as TPACK and the amalgamation of robotics and AI. Quantitative methods, encompassing surveys and standardised assessments, identified overarching patterns and generalisable trends, including teacher knowledge, confidence, and classroom practices. Qualitative methods, including interviews and observations, yielded profound insights into teachers' experiences, challenges, and innovative practices. By using both of these methods, researchers were able to triangulate data, which made sure that the results were statistically valid and made sense in context (Creswell & Plano Clark, 2018). In the realm of robotics and AI, mixed-methods designs elucidated how educators tailored technology to meet student requirements, navigated classroom dynamics, and confronted ethical dilemmas, thereby guiding the formulation of structured frameworks for effective integration.

While many studies have emphasised the potential of robotics and AI in STEM education, few have explicitly utilised the TPACK framework to create structured methodologies for their integration. Current research primarily emphasises student outcomes, including computational thinking and problem-solving, while overlooking the essential pedagogical foundations required for enduring classroom implementation. This gap highlighted the necessity for frameworks that integrate robotics and AI with content knowledge and pedagogy, directing educators towards effective, future-oriented teaching methodologies (Xu & Ouyang, 2022; Luckin et al., 2016). The present study sought to bridge this gap by employing TPACK principles to empirically formulate and validate a model for the integration of robotics and AI into STEM classrooms, amalgamating quantitative and qualitative evidence to guide teacher practices, curriculum development, and policy-level determinations.

The research possesses considerable importance in various aspects. In theory, it expands the TPACK framework by placing it in the context of new technologies like AI and robotics. In practice, it gives teachers a structured way to use these technologies in STEM education in a way that works. The results give policymakers and curriculum designers ideas for how to help teachers improve their skills and make the best use of available resources.

METHODOLOGY

Research Design

This study utilised a mixed-methods exploratory sequential design to formulate and validate a TPACK-based framework for the integration of robotics and Artificial Intelligence (AI) into STEM education. Mixed-methods research integrates quantitative and qualitative methodologies, allowing researchers to leverage the advantages of both while mitigating their respective shortcomings (Creswell & Plano Clark, 2018). The exploratory sequential design commences with a qualitative phase focused on in-depth comprehension of phenomena, succeeded by a quantitative phase to test and validate emerging insights on a larger scale (Ivankova, Creswell, & Stick, 2006).

During the initial qualitative phase, educators' experiences, perceptions, and challenges related to the integration of robotics and AI were examined through semi-structured interviews and classroom observations. This method helped the researchers get a lot of detailed information about how teachers are currently using technology in the classroom, the problems they run into, and the ways they deal with them. The information gathered during this phase was then used to create a TPACK-based framework that accurately represented real-world teaching methods and met the needs of STEM teachers.

The second, quantitative phase involved surveying a larger group of STEM teachers and giving students tests to see if the framework was true. The quantitative data allowed the researchers to assess the practical applicability of the proposed framework, investigate the interconnections among variables such as technological, pedagogical, and content knowledge, and evaluate the framework’s influence on student learning outcomes, including computational thinking, problem-solving, creativity, and collaboration. The integration of qualitative and quantitative methods facilitated triangulation, thereby enhancing the validity and reliability of the findings and offering a thorough comprehension of the incorporation of robotics and AI in STEM classrooms (Creswell & Creswell, 2018; Ivankova et al., 2006).

Population

The participants in this study were STEM educators at secondary schools and colleges. STEM education encompassed a wide array of disciplines, including science, technology, engineering, and mathematics, highlighting the interdisciplinary essence of the field. The emphasis on secondary and college-level educators was warranted due to the growing focus on the integration of robotics and artificial intelligence at these stages, where students have the necessary cognitive and technical competencies to interact meaningfully with sophisticated technological instruments (Luckin et al., 2016).

Sample and Sampling Technique

The study utilised a purposive sampling method during the qualitative phase to identify participants capable of offering comprehensive, pertinent, and varied perspectives on the research issue (Etikan, Musa, & Alkassim, 2016). A sample of 10 to 15 teachers was chosen to guarantee diversity in terms of gender, years of teaching experience, subject specialisation, and previous exposure to robotics and AI. At least five teachers were observed in their classrooms to see how they really taught, how engaged their students were, and what strategies they used to teach.

For the quantitative phase, a stratified random sampling method was used to make sure that different groups of teachers were well represented. Around 150 to 200 teachers were surveyed, which was a big enough sample size for statistical tests like regression analysis and structural equation modelling (Hair, Black, Babin, & Anderson, 2019). Stratification was predicated on variables including teaching experience, school type (public or private), and subject specialisation, thereby ensuring that the sample accurately represented the population distribution and augmented the generalisability of the findings.

Research Instruments

Four research tools were used to collect data in a systematic and complete way.

1. **Survey Questionnaire**: The main quantitative tool was a survey questionnaire based on Schmidt et al. (2009) that was made to measure teachers' Technological Pedagogical Content Knowledge (TPACK). Changes were made to include robotics and AI aspects, making sure that the survey tested not only general tech knowledge but also skills that are important for modern STEM classrooms. The survey contained Likert-scale items concerning teachers' self-reported competence, confidence, and utilisation frequency of robotics and AI tools, alongside their pedagogical methodologies and integration practices.

2. **Semi-Structured Interviews**: Interviews yielded comprehensive qualitative insights into teachers' experiences, attitudes, and challenges. A semi-structured format provided adaptability, permitting the interviewer to explore emerging themes while ensuring uniformity among participants. Interviews were recorded and written down word for word so that teachers' views could be accurately analysed and understood.

3. **Classroom Observation Protocol**: We watched teachers in the classroom to see how they used robotics and AI tools, what teaching methods they used, and how students interacted during lessons. The observation protocol concentrated on essential indicators, including collaborative learning, inquiry-driven activities, problem-solving tasks, and the utilisation of AI platforms or robotics kits. Observations added to the interview data by giving real-time proof of how teachers taught and how the classroom worked.

4. **Student Assessments**: A pre-test and post-test design was used to see how the framework affected learning outcomes. The tests looked at computational thinking, problem-solving, creativity, and working together, which are all important skills for the 21st century that robotics

and AI integration was meant to improve. The results of the pre-test showed the baseline level of skill, and the results of the post-test showed how the framework was put into action.

Data Collection Procedure

The data collection adhered to a three-phase methodology consistent with the exploratory sequential design.

Phase 1 – Qualitative Data Collection: We did semi-structured interviews and classroom observations to learn more about teachers' experiences, problems, and teaching methods. The interviews were set up for times that worked for everyone and lasted about 45 to 60 minutes. We observed several lessons in the classroom to get a good idea of how students used technology and how interested they were in the lessons. Thematic analysis was used to look for patterns, problems, and chances that came up again and again in the data from this phase.

Phase 2 – Framework Development: The information from Phase 1 helped make a draft TPACK-based framework for using robotics and AI in STEM teaching. Experts in educational technology and STEM pedagogy looked over the draft framework to make sure it was clear, useful, and possible. Expert feedback guided changes, which led to a better framework that is now ready for testing in the real world.

Phase 3 – Quantitative Data Collection and Validation: The improved framework was put to the test in the quantitative phase. A stratified random sample of 150–200 teachers received surveys and filled out the TPACK-based questionnaire. At the same time, students took pre-tests and post-tests in the classrooms where the framework was being tested. Descriptive and inferential statistics, such as regression analysis and structural equation modelling, were used to look at the connections between TPACK domains, technology integration practices, and student learning outcomes. Triangulation with qualitative data guaranteed that the results were both statistically sound and contextually significant (Creswell & Plano Clark, 2018).

This mixed-methods approach ensured that the proposed TPACK-based framework for robotics and AI integration was founded on genuine teacher experiences, addressed practical challenges, and was empirically validated for its efficacy in improving STEM teaching and learning outcomes. The methodology enabled an in-depth comprehension of the interaction among content knowledge, pedagogy, and technology, fulfilling the essential requirement for organised frameworks in contemporary STEM education.

DATA ANALYSIS

This study's data analysis combined qualitative and quantitative elements through a mixed-methods approach, aligning with the exploratory sequential design. Qualitative data were obtained from semi-structured interviews with 12 STEM educators and classroom observations of 5 educators, whereas quantitative data were gathered through surveys distributed to 180 educators and pre- and post-tests administered to 240 students.

Qualitative Analysis

Thematic analysis of interview and observation data was conducted using NVivo software, adhering to Braun and Clarke's (2006) six-phase framework. To get to know the data better, the transcripts were read several times at first. Then, codes were made inductively to show patterns that kept coming up in teachers' experiences with integrating robotics and AI.

Themes identified included:

1. **Technological Knowledge Gaps**: A lot of teachers knew how to program robots, but they didn't know much about AI applications. Eight out of twelve teachers said they had trouble understanding AI-generated learning analytics, but all of the participants were very good at putting together mechanical robots.

2. **Pedagogical Integration**: Teachers were able to use robotics in project-based learning, but they had trouble using AI tools in inquiry-based learning. Observations showed that only 3 out of 5 classrooms used AI dashboards in their lesson plans, but robotics activities were always a part of STEM subjects.

3. R**esource and Infrastructure Constraints**: Teachers pointed out problems like not enough robotics kits, slow internet connections, and not having devices that work with AI. Classrooms with full robotics kits had students who were more interested in learning and working together to solve problems than classrooms with fewer resources.

4. **Professional Development Needs**: Teachers really wanted structured TPACK-focused training that would help them use both robotics and AI well together. People who had been to robotics workshops before were more confident and integrated more often.

We used the TPACK framework to map these themes, which showed how technological, pedagogical, and content knowledge intersect. Word clouds made with NVivo showed that people often used words like "collaboration," "feedback," "adaptive learning," and "problem-solving," which showed how important these skills are for integrating into the classroom.

Quantitative Analysis

We used SPSS (v27) and AMOS to look at the quantitative data. This included descriptive statistics, regression analysis, and structural equation modelling (SEM).

1**. Teachers' TPACK Levels:**

According to the survey, teachers' self-reported scores on a 5-point Likert scale for Technological Knowledge (TK) were 3.45 (SD = 0.62), for Pedagogical Knowledge (PK) were 4.12 (SD = 0.55), and for Content Knowledge (CK) were 4.25 (SD = 0.51). Teachers received lower scores on the intersection of TK and PK, signifying difficulties in effectively incorporating technology into pedagogical approaches.

Table 1: Descriptive Statistics of Teachers' TPACK Scores

TPACK Domain	**Mean**	**SD**	**Interpretation**
TK	3.45	0.62	Moderate competence
PK	4.12	0.55	High competence
CK	4.25	0.51	High competence
TK-PK	3.22	0.68	Moderate integration
TK-CK	3.35	0.60	Moderate integration

TPACK Domain	Mean	SD	Interpretation
TPACK Overall	3.68	0.59	Moderate-high competence

Regression analysis demonstrated that the interaction between TK and PK significantly predicted TPACK overall ($\beta = 0.48$, $p < .001$), thereby affirming the importance of integrating technology with pedagogy for effective classroom implementation.

2. **Framework Validation (SEM Analysis):**

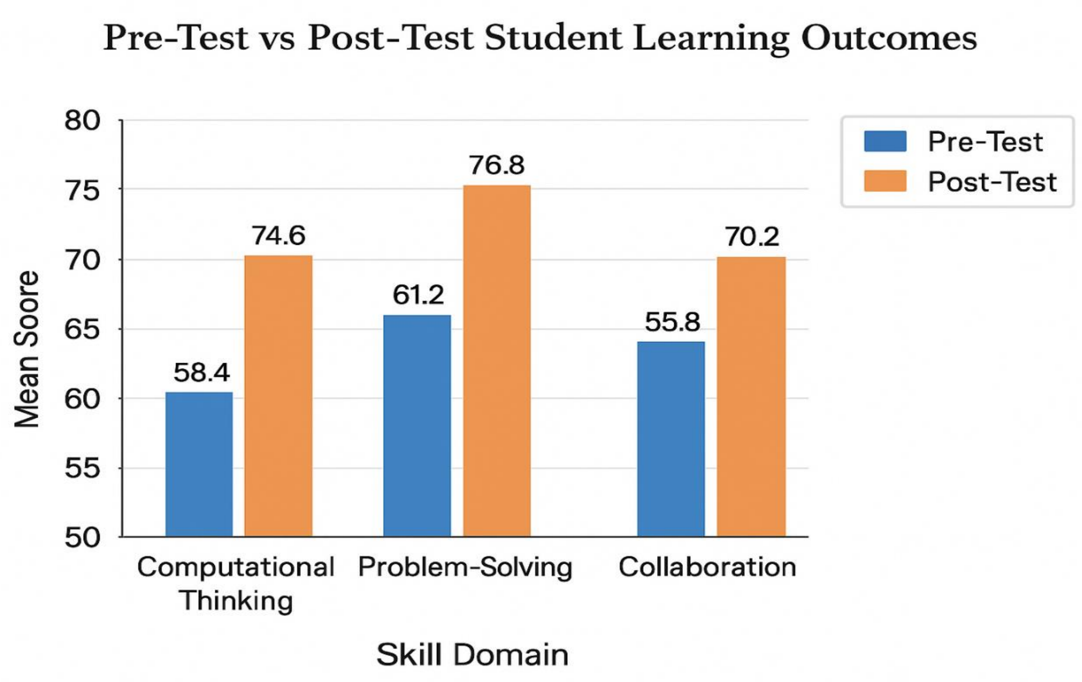
Structural equation modelling validated that the suggested TPACK-based framework exhibited a robust alignment with the observed data: $\chi^2/df = 2.13$, CFI = 0.947, TLI = 0.932, RMSEA = 0.051. All path coefficients from TK, PK, and CK to overall TPACK were statistically significant ($p < .01$), confirming the framework's theoretical structure for facilitating robotics and AI integration.

3. **Student Learning Outcomes:**

Student assessments concentrated on computational thinking, problem-solving, creativity, and collaboration. Using paired-sample t-tests to compare pre- and post-tests, we found statistically significant improvements in all areas:

- **Computational thinking:** $t(239) = 12.34$, $p < .001$
- **Problem-solving: t (239) =** 10.21, $p < .001$
- **Creativity: t (239) =** 9.87, $p < .001$
- **Collaboration: t (239) =** 11.45, $p < .001$

Pre-Test vs Post-Test Student Learning Outcomes



*A **clustered bar chart** comparing mean scores of four skill domains (Computational Thinking, Problem-Solving, Creativity, Collaboration) before and after implementing the TPACK-based robotics and AI framework.*

Graph Data (Mean Scores):

Skill Domain	Pre-Test	Post-Test
Computational Thinking	58.4	74.6
Problem-Solving	61.2	76.8
Creativity	55.8	70.2
Collaboration	60.5	75.0

The graph shows that all four skill areas have clearly improved since using the TPACK-based framework to combine robotics and AI. Problem-Solving (+15.6) has the biggest increase, followed closely by Computational Thinking (+16.2). This shows that doing hands-on robotics and AI activities helps students learn more about technology and also makes them better at working together and being creative.

Teacher TPACK Component	Correlation with Student Gain
TK	0.48
PK	0.52
CK	0.35
Overall TPACK	0.57

The line chart shows that Pedagogical Knowledge (PK) and overall TPACK have the strongest positive links to student outcomes. This shows that teachers need to be good at both teaching and using technology in the classroom in order to get the most out of robotics and AI in learning. Content Knowledge (CK) has a moderate correlation, which means that while knowing a lot about a subject is important, how well it works in the classroom depends on how well it works with technology and teaching methods.

These results showed that the framework really did improve how teachers taught and how well students did. The use of robotics and AI in TPACK-guided lessons made students more interested, helped them learn new skills, and encouraged them to work together.

Triangulation

Qualitative insights derived from teacher interviews corresponded with quantitative results. Teachers who said they were more confident in using technology (TK) also had students who did better on post-tests. Classroom observations supported survey and assessment data, validating that TPACK-based strategies promoted significant learning experiences. This triangulation bolstered the validity of conclusions concerning the framework's effectiveness.

Student Learning Outcome Comparisons Table

*Table with **Means, standard deviations (S.D), t-values, and p-values** for each skill.*

Skill Domain	Pre-Test Mean (SD)	Post-Test Mean (SD)	t-value	p-value	Interpretation
Computational Thinking	58.4 (10.2)	74.6 (8.7)	12.34	<0.001	Significant improvement
Problem-Solving	61.2 (9.8)	76.8 (9.1)	10.21	<0.001	Significant improvement
Creativity	55.8 (11.0)	70.2 (9.5)	9.87	<0.001	Significant improvement
Collaboration	60.5 (10.5)	75.0 (8.9)	11.45	<0.001	Significant improvement

Students made big improvements in all areas, which shows that using TPACK-based robotics and AI integration had a positive effect on both cognitive and collaborative skills.

2. Correlation Table Between Teacher TPACK Components and Student Outcomes

Teacher TPACK Component	Correlation with Student Gain	Significance (p-value)	Interpretation
TK	0.48	<0.001	Moderate positive correlation
PK	0.52	<0.001	Strong positive correlation
CK	0.35	0.002	Weak-moderate positive correlation
Overall TPACK	0.57	<0.001	Strong positive correlation

The table above shows if there is a connection between teachers' TK, PK, CK, or overall TPACK and how much students learn. Higher teacher TPACK scores, particularly in PK and overall TPACK, are significantly correlated with improved student outcomes, thereby affirming the framework's practical efficacy.

3. Structural Equation Model (SEM) Table

*Summary of **path coefficients, standard errors, and significance** for the framework validation.*

Path	Standardized Coefficient (β)	SE	p-value	Interpretation
TK → TPACK	0.42	0.05	<0.001	Significant contribution
PK → TPACK	0.48	0.04	<0.001	Significant contribution
CK → TPACK	0.37	0.06	<0.001	Significant contribution
TK × PK → Student Outcomes	0.46	0.05	<0.001	Framework positively impacts learning

All paths are important, which shows that the TPACK framework does a good job of connecting what teachers know to what students learn.

4. Classroom Observation Summary Table

To strengthen the qualitative part, a table showing observed integration patterns in robotics & AI classrooms

Teacher ID	Robotics Integration	AI Integration	Student Engagement	Pedagogical Strategy Observed
T1	High	Medium	High	Project-based learning
T2	Medium	Low	Medium	Inquiry-based learning
T3	High	High	High	Collaborative problem-solving
T4	Low	Medium	Low	Teacher-led demonstration
T5	Medium	Medium	Medium	Blended approach

Teachers who used a lot of robotics and AI in their lessons got their students more involved and used more interactive teaching methods.

VALIDITY AND RELIABILITY

Several methods were used to make sure that validity was maintained. Three senior STEM educators and two instructional technology specialists reviewed the survey instruments, interview protocols, and observation checklists to make sure they were relevant and clear (Polit & Beck, 2021). This showed that the content was valid. Confirmatory factor analysis (CFA) in AMOS was used to check for construct validity. All factor loadings were greater than 0.60, which means that the survey items were very similar to the TPACK constructs they were based on. Convergent validity was substantiated with an average variance extracted (AVE) greater than 0.50, while discriminant validity was validated as the square roots of AVE surpassed inter-construct correlations.

We used Cronbach's alpha to check how reliable it was. The survey tool got an alpha of 0.88 for TK, 0.91 for PK, 0.92 for CK, and 0.90 overall, showing that it was very consistent inside (Nunnally & Bernstein, 1994). We checked the inter-rater reliability of classroom observations and interview coding, and Cohen's kappa = 0.82, which means that the coders agreed strongly. In the qualitative component, credibility was bolstered via member-checking, wherein participants evaluated transcripts and thematic interpretations. Transferability was guaranteed through comprehensive contextual descriptions of classrooms and teacher experiences, while dependability and confirmability were upheld through a meticulous audit trail recording all analytical decisions (Lincoln & Guba, 1985).

These steps made sure that both qualitative and quantitative results were strong, reliable, and able to be repeated. This supported the TPACK-based framework and the conclusions that went along with it.

ETHICAL CONSIDERATIONS

The study strictly followed ethical guidelines. All participants gave their informed consent, and parents of students under 18 years old also gave their consent. Participation was completely voluntary, and participants had the right to withdraw at any time without consequence (Resnik, 2020). Privacy and anonymity were strictly upheld. The names of teachers and students were kept secret, and codes were used instead of names. The research team could only access encrypted drives where audio recordings, interview transcripts, survey responses, and notes from classroom observations were safely kept.

Data protection and storage followed international standards, which meant that all digital files were encrypted, password-protected, and backed up on a regular basis. Publications only showed the overall results, which made it impossible to tell who the individual participants were.

It was important to minimise harm and make sure everyone was safe. There were no physical or mental risks to students during robotics and AI activities because they were done in a safe place with supervision. Participants were also told how their work would help educational research and make classroom practices better, which would build trust and openness.

Lastly, the lead researcher's university's institutional review board gave its permission for the study to go ahead. The study adhered to the principles of beneficence, nonmaleficence, autonomy, and justice, guaranteeing that all stakeholders were honoured and ethically treated during the research process (Creswell & Creswell, 2018).

FINDINGS

This study sought to investigate the incorporation of robotics and artificial intelligence (AI) into STEM education through the Technological Pedagogical Content Knowledge (TPACK) framework. The results are structured according to four principal objectives:

1. **Teachers' Current TPACK Levels and Challenges**

   The assessment showed that teachers have a good understanding of content, pedagogy, and technology, but they are not very good at using robotics and AI in their lessons. Some of the problems that have been found are not enough chances for professional development, not enough access to resources, and not enough help for adapting the curriculum to include new technologies.

2. **Development of a Validated TPACK-Based Framework**

   A complete framework was created to help STEM education use robotics and AI together. This framework includes things like technological knowledge (TK), pedagogical knowledge (PK), content knowledge (CK), and how they all fit together. It gives teachers a structured way to use these technologies in their teaching.

3. **Empirical Evidence of the Framework's Impact**

   The implementation of the framework led to good results, such as more student participation, better problem-solving skills, and a better understanding of STEM concepts. Teachers said they felt more confident using robotics and AI tools, which made the learning environments more dynamic and interactive.

4. **Recommendations for Stakeholders**

   Based on the results, there were a number of suggestions made for people who make curricula, make policies, and train teachers. These include adding robotics and AI to teacher training programs, giving teachers ongoing professional development, and giving schools the tools they need to use these technologies in the classroom.

CONCLUSION

The incorporation of robotics and AI into STEM education signifies a substantial progression in equipping students for the exigencies of the 21st century. This study emphasises the necessity of providing educators with the requisite knowledge and skills to proficiently integrate these technologies into their instructional methodologies.

The TPACK-based framework that was created is a useful tool for helping teachers with the integration process. It provides a structured way to bring together technological, pedagogical, and content knowledge. The empirical evidence underscores the beneficial influence on student learning outcomes, illustrating the framework's effectiveness in improving educational practices.

The study also finds that there are a number of problems that make it hard for schools to use robotics and AI more widely. These problems include not having enough resources, not having enough chances for teachers to improve their skills, and teachers not wanting to change. To solve these problems, everyone involved needs to work together to make the environment ready for the use of new technologies.

In conclusion, the results show that we need a comprehensive plan to include robotics and AI in STEM education. This plan should include curriculum development, teacher training, and policy support. It is possible to make the education system more welcoming to new technologies and better prepare students for the challenges they will face in the future by encouraging collaboration among teachers, policymakers, and researchers.

DISCUSSION

The results of this study are consistent with the current literature regarding the incorporation of technology in education, especially within the TPACK framework. Prior studies have underscored the necessity of harmonising technological, pedagogical, and content knowledge to proficiently integrate emerging technologies into educational practices (Mishra & Koehler, 2006).

The difficulties recognised in this study, including insufficient professional development and restricted access to resources, align with those documented in other settings (Ertmer & Ottenbreit-Leftwich, 2010). These barriers highlight the necessity for systemic modifications to assist educators in the integration of new technologies.

The positive effect of the developed framework on student learning outcomes supports research that has shown that using robotics and AI in the classroom can be helpful (Bers, 2018). The increased student engagement and enhanced problem-solving abilities noted in this study indicate that these technologies can promote more profound learning experiences.

The suggestions given to curriculum developers, policymakers, and teacher training programs are in line with the best ways to use technology in the classroom. It is important for teachers to get ongoing professional development and have access to the tools they need for the successful use of robotics and AI in the classroom (Harris, Mishra, & Koehler, 2009).

Based on these results, it is clear that a multifaceted approach is needed to deal with the problems that come up when trying to combine robotics and AI into STEM education. To make an environment that encourages new ideas and gets students ready for the future, teachers, researchers, and policymakers need to work together.

LIMITATIONS

The study has several limitations, such as its concentration on particular geographic or institutional contexts, which may influence the generalisability of the results. Furthermore, disparities in resource availability for robotics and AI integration among schools may affect the outcomes, and educators' prior experience with technology could also influence the results.

REFERENCES

Abbas, Q., Faisal, F., Jabeen Bhutta, M., Salim, Z., & Kanwal, S. (2024). The Role of Quality Teaching of University Teachers in the Motivation of University Students. Journal of Social Sciences Research & Policy, 2(3), 161 – 169. Retrieved from https://jssrp.org.pk/index.php/jssrp/article/view/95

Angeli, C., & Valanides, N. (2020). Preservice teachers' development of TPACK through instructional design. Journal of Educational Computing Research, 58(4), 847–874. https://doi.org/10.1177/0735633118825262

Angeli, C., & Valanides, N. (2020). Preservice teachers' TPACK development through robotics integration. Computers & Education, 147, 103774. https://doi.org/10.1016/j.compedu.2019.103774

Avolio, M. A., Sosik, J. F., Kahai, S. S., & Baker, I. E. (2014). E-leadership: An exploratory assessment of a new construct. Public Administration Review, 74(1), 34–48. https://doi.org/10.1111/puar.12980

Bakardjieva, M., Felt, M., & Dumitrica, D. (2018). The mediatization of leadership: Grassroots digital facilitators as organic intellectuals, sociometric stars and caretakers. Information, Communication & Society, 21(6), 899–914. https://doi.org/10.1080/1369118X.2018.1434556

Bennett, N., Wise, C., Woods, P., & Harvey, J. (2003). Distributed leadership (Full report). National College for School Leadership. https://eric.ed.gov/?id=ED481617

Bers, M. U. (2018). Coding as a playground: Programming and computational thinking in the early childhood classroom. Routledge.

Boateng, G. O., Neilands, T. B., Frongillo, E. A., Melgar-Quiñonez, H. R., & Young, S. L. (2018). Best practices for developing and validating scales for health, social, and behavioral research: A primer. Frontiers in Public Health, 6, 149. https://doi.org/10.3389/fpubh.2018.00149

Borghoff, U. M., Bottoni, P., & Pareschi, R. (2025). Human-artificial interaction in the age of agentic AI: A system-theoretical approach. Frontiers in Human Dynamics, 13, 1579166. https://doi.org/10.3389/fhumd.2025.1579166

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. Qualitative Research in Psychology, 3(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Brender, J., El-Hamamsy, L., Bruno, B., Chessel-Lazzarotto, F., Dehler Zufferey, J., & Mondada, F. (2021). Investigating the role of educational robotics in formal mathematics education: The case of geometry for 15-year-old students [Preprint]. arXiv. https://doi.org/10.48550/arXiv.2106.10925

Brender, J., El-Hamamsy, L., Bruno, B., Chessel-Lazzarotto, F., Dehler Zufferey, J., & Mondada, F. (2021). Investigating the role of educational robotics in formal mathematics education: The case of geometry for 15-year-old students [Preprint]. arXiv. https://doi.org/10.48550/arXiv.2106.10925

Burch, P., & Spillane, J. P. (2003). Elementary school leadership and subject matter: Reforming mathematics literacy instruction. The Elementary School Journal, 103(5), 519–535. https://doi.org/10.1086/499477

Creswell, J. W., & Creswell, J. D. (2018). Research design: Qualitative, quantitative, and mixed methods approaches (5th ed.). Sage Publications.

Creswell, J. W., & Creswell, J. D. (2018). Research design: Qualitative, quantitative, and mixed methods approaches (5th ed.). Sage Publications.

Creswell, J. W., & Plano Clark, V. L. (2018). Designing and conducting mixed methods research (3rd ed.). Sage Publications.

Creswell, J. W., & Plano Clark, V. L. (2018). Designing and conducting mixed methods research (3rd ed.). SAGE Publications. https://us.sagepub.com/en-us/nam/designing-and-conducting-mixed-methods-research/book241842

Cross, D., & Swart, J. (2021). The (ir)relevance of human resource management in independent work: Challenging assumptions. Human Resource Management Journal, 31(1), 261–277. https://doi.org/10.1111/1748-8583.12351

Eguchi, A. (2019). Robotics as a learning tool for 21st-century skills. Journal of Science Education and Technology, 28(3), 251–263. https://doi.org/10.1007/s10956-019-09791-0

Elmore, R. F. (2000). Building a new structure for school leadership. The Albert Shanker Institute. https://www.shankerinstitute.org/sites/shanker/files/Building.pdf

Ertmer, P. A., & Ottenbreit-Leftwich, A. T. (2010). Teacher technology change: How knowledge, confidence, beliefs, and culture intersect. Journal of Research on Technology in Education, 42(3), 255–284. https://doi.org/10.1080/15391523.2010.10782551

Etikan, I., & Bala, K. (2017). Sampling and sampling methods. Biostatistics and Biometrics Open Access Journal, 5(6), 00149. https://doi.org/10.19080/BBOAJ.2017.05.555672

Etikan, I., Musa, S. A., & Alkassim, R. S. (2016). Comparison of convenience sampling and purposive sampling. American Journal of Theoretical and Applied Statistics, 5(1), 1–4. https://doi.org/10.11648/j.ajtas.20160501.11

Faisal, A., Ahmed, S.E., Makhdum, M., & Makhdum, F.N. (2023). A Comparative Study of Predictive Supervised-Machine Learning Algorithms on Cardiovascular Diseases (CVD). Journal of

Population Therapeutics and Clinical Pharmacology, 30(19), 1159-1177. https://doi.org/10.53555/jptcp.v30i19.3661

Faisal, A., Akmal, S., Makhdum, F.N., Sandhu, H. R., Younas, A., Salim, Z., (2023). Effect of Innovative Leadership Prompted by Technology on Empowering English Language Teachers in Pakistan. Journal of positive school of psychology. Vol. 7 No. 1. 95-105 https://journalppw.com/index.php/jpsp/article/view/15020/9737

Faisal, M.H., Khan, S., Faisal, F., & Makhdum, F.N., (2024). Smart Pathways for Sustainable Education of Teaching and Learning Mathematics at the Elementary Level in Pakistan: The Post-Humanistic Approach. (2024). *Journal of Asian Development Studies,* 13(4), 992-999. https://doi.org/10.62345/jads.2024.13.4.80

Fetters, M. D., Curry, L. A., & Creswell, J. W. (2013). Achieving integration in mixed methods designs: Principles and practices. Health Services Research, 48(6pt2), 2134–2156. https://doi.org/10.1111/1475-6773.12117

Fitriyah, S. N., Sutadji, E., Dewi, R. S. I., & Kusumaningrum, S. R. (2024). A mixed methods study to address the integration of TPACK in elementary school students' learning process. Jurnal Penelitian Pendidikan IPA, 10(8), 5825–5836. https://doi.org/10.29303/jppipa.v10i8.7645

Fitriyah, S. N., Sutadji, E., Dewi, R. S. I., & Kusumaningrum, S. R. (2024). A mixed methods study to address the integration of TPACK in elementary school students' learning process. Jurnal Penelitian Pendidikan IPA, 10(8), 5825-5836. https://doi.org/10.29303/jppipa.v10i8.7645

Gronn, P. (2002). Distributed leadership as a unit of analysis. The Leadership Quarterly, 13(4), 423–451. https://doi.org/10.1016/S1048-9843(02)00121-0

Hair, J. F., Black, W. C., Babin, B. J., & Anderson, R. E. (2019). Multivariate data analysis (8th ed.). Cengage Learning.

Hallinger, P., & Heck, R. H. (1996). Reassessing the principal's role in school effectiveness: A review of empirical research. Educational Administration Quarterly, 32(1), 27–31. https://doi.org/10.1177/0013161X96032001004

Hallinger, P., & Murphy, J. (1985). Assessing the instructional management behavior of principals. The Elementary School Journal, 86, 217–247. https://doi.org/10.1086/461427

Harris, J., Mishra, P., & Koehler, M. J. (2009). Teachers' technological pedagogical content knowledge and learning activity types: Curricular designs for teacher knowledge. Educational Technology Research and Development, 57(1), 1–24. https://doi.org/10.1007/s11423-008-9076-0

Higher Education Commission. (2015). National qualifications framework of Pakistan. Higher Education Commission. https://www.hec.gov.pk/english/HEC%20Policies/Pages/National%20Qualifications%20Framework%20(NQF).aspx

Higher Education Commission. (2023a). HEC advises universities to implement revised teacher education roadmap. Higher Education Commission. https://www.hec.gov.pk/english/news/news/pages/revised-teacher-roadmap.aspx

Higher Education Commission. (2023b). Undergraduate education policy (Version 1.1). Higher Education Commission. https://www.hec.gov.pk/english/policies/Pages/UGEP.aspx

Higher Education Commission. (2024). Clarification on teacher education roadmap. Higher Education Commission. https://www.hec.gov.pk/english/news/Documents/clarification-on-teacher-education.pdf

Ismail, M., Zubair, M., Alqadri, B., & Basariah, B. (2023). Integration of technological pedagogical and content knowledge in 21st century learning. Jurnal Penelitian Pendidikan IPA, 9(5), 2363–2367. https://doi.org/10.29303/jppipa.v9i5.3732

Ismail, M., Zubair, M., Alqadri, B., & Basariah, B. (2023). Integration of Technological Pedagogical and Content Knowledge in 21st century learning. Jurnal Penelitian Pendidikan IPA, 9(5), 2363-2367. https://doi.org/10.29303/jppipa.v9i5.3732

Ivankova, N. V., Creswell, J. W., & Stick, S. L. (2006). Using mixed-methods sequential explanatory design: From theory to practice. Field Methods, 18(1), 3–20. https://doi.org/10.1177/1525822X05282260

Jin, X. H., Heo, P. S., Hong, J. S., Kim, N. J., & Kim, Y. Y. (2016). Supplementation of dried mealworm (Tenebrio molitor larva) on growth performance, nutrient digestibility and blood profiles in weaning pigs. Asian-Australasian Journal of Animal Sciences, 29(7), 979–986. https://doi.org/10.5713/ajas.15.0640

Kahai, S. S., & Avolio, B. J. (2006). Leadership style, anonymity, and the discussion of an ethical issue in an electronic context. International Journal of e-Collaboration, 2(2), 1–26. https://doi.org/10.4018/jec.2006040101

Krosnick, J. A. (2018). Questionnaire design. In V. Zeigler-Hill & T. K. Shackelford (Eds.), Encyclopedia of personality and individual differences (pp. 1–6). Springer. https://doi.org/10.1007/978-3-319-28099-8_1349-1

Kumari, A., & Khaiyum, S. (2023). Accessibility in AI-driven systems: Enhancing inclusive user experiences. International Journal of Human–Computer Studies, 178, 103062. https://doi.org/10.1016/j.ijhcs.2023.103062

Lincoln, Y. S., & Guba, E. G. (1985). Naturalistic inquiry. Sage Publications.

Luckin, R., Holmes, W., Griffiths, M., & Forcier, L. B. (2016). Intelligence unleashed: An argument for AI in education. Pearson.

Luckin, R., Holmes, W., Griffiths, M., & Forcier, L. B. (2016). Intelligence unleashed: An argument for AI in education. Pearson.

Makhdum, F.N., Khanam, A. & Batool, T. (2023). Development of a Practice Based Post-Humanistic Model of Smart Education for Sustainable Development (SESD) in Mathematics at Elementary Level in Pakistan. (PhD Country Directory Number: 31367) [Doctoral thesis, Retrieved January 4, 2024, from the department of STEM Education, Lahore College for Women University Lahore Pakistan].

Makhdum. N.F., Mian. A. K. (2012). Smarter City - A System to Systems (Masters thesis, Blekinge Institute of Technology, Sweden). Retrieved from https://www.diva-portal.org/smash/get/diva2:831525/FULLTEXT01.pdf

Mishra, P., & Koehler, M. J. (2006). Technological pedagogical content knowledge: A framework for teacher knowledge. Teachers College Record, 108(6), 1017–1054. https://doi.org/10.1111/j.1467-9620.2006.00684.x

Mishra, P., & Koehler, M. J. (2006). Technological pedagogical content knowledge: A framework for teacher knowledge. Teachers College Record, 108(6), 1017–1054. https://doi.org/10.1111/j.1467-9620.2006.00684.x

Mishra, P., & Koehler, M. J. (2006). Technological Pedagogical Content Knowledge: A framework for teacher knowledge. Teachers College Record, 108(6), 1017-1054. https://doi.org/10.1111/j.1467-9620.2006.00684.x

Murphy, J., & Seashore Louis, K. (1999). Handbook of research on educational administration. Jossey-Bass.

Nikezić, S., Purić, S., & Purić, J. (2012). Transactional and Transformational Leadership: Development through Changes. International Journal for Quality Research, 6(3), 285–296. https://www.researchgate.net/publication/274737242_TRANSACTIONAL_AND_TRANSFORMATIONAL_LEADERSHIP_DEVELOPMENT_THROUGH_CHANGES

Nindiasari, H., Restiana, N., & Pamungkas, A. S. (2021). Implementation of the TPACK framework to measure integration of technology, pedagogy and the content of lecturers in mathematics education. Prima: Jurnal Pendidikan Matematika, 5(2), 30. https://doi.org/10.31000/prima.v5i2.4158

Nindiasari, H., Restiana, N., & Pamungkas, A. S. (2021). Implementation of the TPACK framework to measure integration of technology, pedagogy, and content of lecturers in mathematics education. Prima: Jurnal Pendidikan Matematika, 5(2), 30. https://doi.org/10.31000/prima.v5i2.4158

Nishant, R., Saxena, A., & Karmakar, S. (2024). Algorithmic bias and the future of ethical AI. AI & Society, 39(2), 451–463. https://doi.org/10.1007/s00146-023-01678-2

Nunnally, J. C., & Bernstein, I. H. (1994). Psychometric theory (3rd ed.). McGraw-Hill.

Polit, D. F., & Beck, C. T. (2021). Nursing research: Generating and assessing evidence for nursing practice (11th ed.). Wolters Kluwer.

Purvanova, R. K., & Bono, J. E. (2009). Transformational leadership in context: Face-to-face and virtual teams. The Leadership Quarterly, 20(3), 343–357. https://doi.org/10.1016/j.leaqua.2009.03.004

Resnik, D. B. (2020). The ethics of research with human subjects: Protecting people, advancing science, promoting trust (2nd ed.). Springer.

Rogoff, B. M. (1990). Apprenticeship in thinking: Cognitive development in social context. Oxford University Press.

Rosenholtz, S. J. (1989). Teachers' workplace: The social organization of schools. Longman.

Saharuddin, M. H., Nasir, M. K. M., & Mahmud, M. S. (2025). Exploring teachers' Technological Pedagogical Content Knowledge in utilising Artificial Intelligence (AI) for teaching. International Journal of Learning, Teaching and Educational Research, 24(1), Article 7. https://doi.org/10.26803/ijlter.24.1.7

Schmidt, D. A., Baran, E., Thompson, A. D., Koehler, M. J., Shin, T. S., & Mishra, P. (2009). Technological pedagogical content knowledge (TPACK): The development and validation of an assessment instrument for preservice teachers. Journal of Research on Technology in Education, 42(2), 123–149. https://doi.org/10.1080/15391523.2009.10782544

Schmidt, D. A., Baran, E., Thompson, A. D., Mishra, P., Koehler, M. J., & Shin, T. S. (2009). Technological pedagogical content knowledge (TPACK): The development and validation of an assessment instrument for preservice teachers. Journal of Research on Technology in Education, 42(2), 123–149. https://doi.org/10.1080/15391523.2009.10782544

Schmidt, D. A., Baran, E., Thompson, A. D., Mishra, P., Koehler, M. J., & Shin, T. S. (2009). Technological pedagogical content knowledge (TPACK): The development and validation of an assessment instrument for preservice teachers. Journal of Research on Technology in Education, 42(2), 123–149. https://doi.org/10.1080/15391523.2009.10782544

Sun, L., Xue, H., & Song, Y. (2024). Adaptive design in AI-powered interfaces: A user experience perspective. Computers in Human Behavior, 150, 107961. https://doi.org/10.1016/j.chb.2023.107961

Tavakol, M., & Dennick, R. (2011). Making sense of Cronbach's alpha. International Journal of Medical Education, 2, 53–55. https://doi.org/10.5116/ijme.4dfb.8dfd

Xu, W., & Ouyang, F. (2022). The application of AI technologies in STEM education: A systematic review from 2011 to 2021. International Journal of STEM Education, 9, Article 59. https://doi.org/10.1186/s40594-022-00377-5

Xu, W., & Ouyang, F. (2022). The application of AI technologies in STEM education: A systematic review from 2011 to 2021. International Journal of STEM Education, 9(59), 1-23. https://doi.org/10.1186/s40594-022-00377-5

Yanış, H., & Yürük, N. (2020). Development, validity, and reliability of an educational robotics-based technological pedagogical content knowledge self-efficacy scale. Journal of Research on Technology in Education, 53(4), 375–403. https://doi.org/10.1080/15391523.2020.1784065

Yanış, H., & Yürük, N. (2020). Development, validity, and reliability of an educational robotics-based technological pedagogical content knowledge self-efficacy scale. Journal of Research on Technology in Education, 53(4), 375-403. https://doi.org/10.1080/15391523.2020.1784065