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Bridging AI-TPACK and STEM Education: Navigating Facilitators, Barriers, and Ethical Dimensions Through a Systematic Review

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ABSTRACT

Artificial intelligence (AI) can play a transformative role in STEM education, although its integration presents pedagogical, technological, and ethical challenges. This review synthesizes interdisciplinary perspectives on AI integration in K–12 STEM classrooms through the AI Technological Pedagogical Content Knowledge (AI-TPACK) framework. Using PRISMA guidelines, 38 empirical studies published between 2018 and 2025 were analyzed through deductive coding. Findings indicate that AI can support the visualization of STEM content, enable adaptive feedback, and foster collaborative learning environments. However, these opportunities are constrained by infrastructure limitations, insufficient teacher preparation, and misalignment between AI tools and curriculum goals. Ethical concerns related to privacy, bias, and transparency emerged as central challenges. This study offers recommendations for the sustainable integration of AI in STEM education.

Keywords: AI integration, AI-TPACK, Artificial Intelligence, K–12 Education, STEM Education, Systematic Review.

INTRODUCTION

Artificial intelligence (AI) has been introduced as a transformative innovation with the potential to reshape the knowledge and skills required for participation in scientific and technical fields. In STEM learning environments, AI-powered tools help bridge theoretical learning with authentic problem-solving experiences (Chu, 2025), i.e., engaging students with real-world applications of STEM knowledge (Mohamed et al., 2022; Yanar and Ergene, 2025) rather than mechanically following memorized steps. Beyond the empirically supported role of AI in authentic problem-solving, automating feedback (Demszky et al., 2025) and personalizing learning (Xu & Ouyang, 2022), AI also has the potential to reshape core epistemic practices in STEM classrooms (Kim, 2022; Xu & Ouyang, 2022). Epistemic practices refer to the process of thinking, reasoning, and social practices through which knowledge is generated, evaluated, validated, and communicated (Berland et al., 2016; Petit, 2025). The literature indicates that AI can assist teachers in mediating students' engagement (Ajayi, 2024; Haider et al., 2025), computational modeling (Cromley et al., 2023; Lin et al., 2025; Pellas et al., 2020), supporting adaptive scaffolding in metacognitive regulation (Petit, 2025; Shin et al., 2025), and facilitating new forms of data-driven collaboration (Benita et al., 2021), all of which are significant contributors to reshaping epistemic practices in STEM classrooms.

As AI offers significant opportunities to enrich STEM learning, leveraging these capabilities requires preparing teachers for the sustainable integration of AI (Kayaalp et al., 2025; Ning et al., 2024). Integrating AI into STEM education is a complex process that must be pedagogically meaningful and ethically informed, rather than focusing only on the technical aspects of use (Haider et al., 2025; Leon et al., 2025). Without this broader foundation, AI integration may result in a short-term and overly tool-focused approach. Therefore, to enhance the sustainability of AI integration, teacher AI readiness programs should go beyond technical or computational proficiency and include pedagogical reasoning, ethical awareness, and confidence in collaborating with AI systems (Traga Philippakos and Rocconi, 2025; Xu & Ouyang, 2022). Although research on AI integration in STEM education has expanded, existing systematic reviews have largely focused on AI applications (Karthikeyan, 2026; Xu & Ouyang, 2022), perceived benefits and challenges (Nguyen et al., 2025), and teachers' adoption experiences (Kavitha & Joshith, 2024). Yet, there has been a lack of consideration for the interconnected pedagogical, technological, and ethical dimensions required for sustainable AI integration. This gap matters because AI integration in STEM education is not simply a matter of adopting tools. This integration involves teachers' decisions about content, pedagogy, and responsible use in context. The AI-TPACK framework (Ning et al., 2024) builds on this idea by explaining that effective teaching with technology depends on the interaction between three major knowledge domains: content, pedagogical, and technological knowledge, which work together in real classrooms (Ning et al., 2024). Moreover, the effective application of the core TPACK framework in teacher professional development (Koh & Chai, 2016; Mishra & Warr, 2021; Schmidt et al., 2009) demonstrates how structured training can help teachers integrate technological, pedagogical, and content knowledge in practice. This is particularly relevant for AI-TPACK, as AI integration requires teachers to not only understand AI tools (AI-TK), but also align AI integration with instructional strategies (AI-TPK) and disciplinary goals (AI-TCK) (Rajapakse, 2026). Therefore, AI-TPACK extends the original framework by specifying the types of knowledge and competencies teachers need to develop to use AI effectively, thereby justifying its inclusion in this study.

The present systematic review not only synthesizes facilitators, barriers, and ethical considerations related to AI integration in K–12 STEM education but also situates these findings within a modified AI-TPACK framework. It offers an interconnected perspective on achieving sustainable AI integration by reframing this integration as a coordinated, competency-based process rather than an isolated tool adoption. This study has the potential to make two key contributions. Conceptually, it advances existing scholarship by modifying an AI-TPACK framework that articulates the interplay among pedagogical, technological, and ethical dimensions in AI-supported STEM education. In practice, this study provides evidence-based insights into teacher AI readiness and professional learning initiatives to guide effective and sustainable AI integration in future STEM learning environments. To this end, this study addresses the following research questions:

1. What facilitators of AI integration are identified in K–12 STEM education across AI-TPACK domains?
2. What barriers to AI integration are encountered in K–12 STEM education across AI-TPACK domains?
3. What ethical considerations for AI integration are addressed in K–12 STEM education across AI-TPACK domains?

AI-TPACK Framework

As AI continues to introduce new approaches to education, existing technology integration frameworks are also evolving to reflect these transformations. Traditional technology integration models are being reshaped or extended to account for AI-specific dimensions. Among these frameworks, the Technological Pedagogical Content Knowledge (TPACK) model remains foundational for understanding how teachers integrate technology meaningfully into instruction (Ismaniati et al., 2025; Karataş & Ataç, 2025; Schubatzky et al., 2025). According to TPACK, the integration of technology in teaching arises from a deep understanding of three core domains: content knowledge (CK), pedagogical knowledge (PK), and technological knowledge (TK) and the interactions among them including technological pedagogical knowledge (TPK), pedagogical content knowledge (PCK), and technological content knowledge (TCK) (Koehler et al., 2013; Mishra & Koehler, 2006).

Researchers have expanded TPACK to incorporate AI-specific competencies and introduced the AI-TPACK framework. Traditional TPACK conceptualizes technology as a tool that teachers deliberately select and integrate into instruction. However, AI introduces qualitatively different affordances that extend and challenge this assumption. Unlike conventional technologies, AI systems can generate content, provide adaptive feedback, and act with a degree of autonomy in instructional processes. This shifts the role of technology from a passive tool to an active, co-constructive partner in teaching and learning. As a result, effective integration requires not only knowledge of how to use technology but also the ability to critically evaluate, guide, and collaborate with AI systems. Recent literature outlines the importance of AI-TPACK in enabling educators to develop competencies that integrate AI knowledge with pedagogical strategies and content expertise (Karataş & Ataç, 2025; Celik, 2023; Hava & Babayigi, 2025; Ismaniati et al., 2025; Mishra et al., 2023; Ning et al., 2024; Pörn et al., 2024). This model emphasizes that knowing AI tools is not enough for effective AI-supported teaching, and teachers need to coordinate AI capabilities, pedagogy, and content in coherent instructional designs (Celik, 2023; Ning et al., 2024).

In bridging the AI-TPACK framework for STEM education, Content Knowledge (CK) encompasses foundational theories, core concepts, content-specific practices, and epistemological assumptions across science, technology, engineering, and mathematics fields.

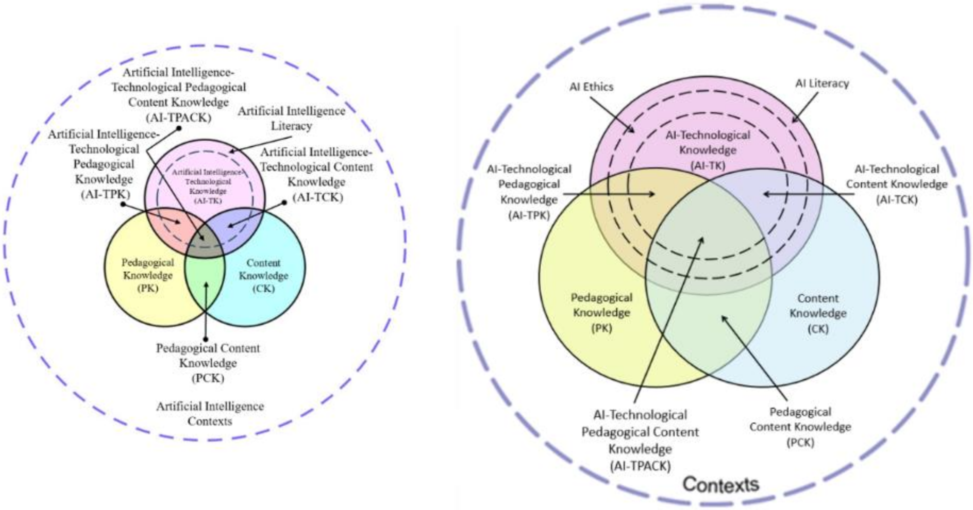
Pedagogical Knowledge (PK) refers to STEM teachers' understanding of how to design lessons using approaches such as inquiry-based learning, the 5E model (Bybee & Landes, 1990), or problem-based instruction, in ways that actively engage students and promote sense-making. In STEM classrooms, teachers apply Pedagogical Content Knowledge (PCK) when they select representations, examples, and analogies that make specific STEM concepts accessible, such as using visual models to explain proportional reasoning in mathematics or concrete simulations to illustrate scientific processes. In STEM contexts, teachers apply AI-Technological Knowledge (AI-TK) when evaluating the reliability and suitability of AI outputs, making informed decisions, and recognizing situations in which AI support may be misleading or inappropriate. These practices provide teachers with the technical awareness necessary to use AI tools confidently, responsibly, and ethically within STEM learning environments. Beyond basic knowledge of AI platforms, tools, and resources, this understanding involves the capacity to adapt and apply AI technologies in educational contexts in ways that support the development of AI literacy (Ning et al., 2024) while fostering ethical awareness of AI use (Hava & Babayigit, 2025). According to Ng et al. (2021), AI literacy is a multifaceted competence aligned with cognitive domains in Bloom's taxonomy, including understanding, applying, evaluating, and creating AI, as well as ethical considerations. From this perspective, AI ethics is not treated as a separate domain but as a constitutive dimension that shapes responsible AI use and defines what it means to be literate in AI (Ng et al., 2021). Therefore, in this study (see Figure 1), AI literacy and AI ethics are conceptualized as two interconnected layers of teacher AI-technological knowledge that shape meaningful and sustainable AI integration in education.

AI-Technological Content Knowledge (AI-TCK) reflects teachers' ability to recognize which AI applications are appropriate for specific STEM concepts, such as using AI-supported simulations to model scientific phenomena, dynamic systems to visualize mathematical relationships, or intelligent coding environments to support algorithmic thinking. Similarly, in STEM classrooms, AI-Technological Pedagogical Knowledge (AI-TPK) emphasizes the effective use of AI tools to design personalized, interactive, inquiry-based, and self-paced learning experiences that align with learners' knowledge levels, cognitive readiness, and learning needs (Cao et al., 2026; Celik, 2023). Finally, AI-Technological Pedagogical Content Knowledge (AI-TPACK) represents the integrated knowledge that teachers draw upon when designing instruction that brings together disciplinary content, pedagogy, and AI technologies in meaningful ways. This core knowledge domain captures how teachers leverage AI technologies not merely as instructional aids, but as cognitive and pedagogical resources that shape how knowledge is developed, represented, and learned in subject-specific contexts (Celik, 2023; Ning et al., 2024).

In addition to considering the meaning and application of the domains mentioned, another important nuance is context. This framework is inherently shaped by broader contextual conditions, and as Kelly (2010) stated, the enactment of these domains and the ways they will be applied depend on context. Also, Rosenberg and Koehler (2015) highlighted that context consists of subject matter, grade level, and institutional and societal factors. Therefore, this study focused on the AI-TPACK framework within K–12 STEM classroom contexts. In this study, as shown in Figure 1, the AI-TPACK framework was revised to better capture AI-specific competencies. The revision focuses on the technological knowledge domain (AI-TK). In the modified model, AI-TK is treated as a multi-layered domain. The former AI-TPACK considers AI literacy a core layer of technological knowledge, and we have embedded AI ethics within this layer. This decision is grounded in the AI literacy literature, which views ethical understanding as an essential part of AI literacy, instead of a separate component (Lin et al., 2025; Long & Magerko, 2020; Ng et al., 2021; Traga Philippakos and Rocconi, 2025). Adding AI ethics to AI-TPACK enables us to more accurately capture how teachers engage with AI tools in practice, where technical use and ethical judgment are deeply intertwined.

Figure 1

AI-TPACK Framework by Ning et al. (2024) (Left) and the Authors' Modified AI-TPACK Framework (Right)



RESEARCH METHOD

This study employed a systematic literature review design, following the Preferred Reporting Items for Systematic Reviews (PRISMA 2020) (Page et al., 2021), to synthesize empirical research on the integration of AI in K–12 STEM education. By following PRISMA guidelines, we could conduct a systematic and transparent search to synthesize empirical evidence on facilitators, barriers, and ethical considerations of AI integration in STEM education. The review covered peer-reviewed studies published between 2018, marking the emergence of generative AI, and 2025. The systematic review proceeded through four structured phases: study identification, screening, eligibility assessment, and inclusion (Page et al., 2021). To analyze findings across studies, a deductive coding approach was used, guided by the modified AI-TPACK framework, which provided theoretically informed dimensions for organizing and interpreting the results.

Search Strategy

Since systematic reviews should integrate both specialized and broad databases (Gusenbauer & Haddaway, 2020), we prioritized databases with multidisciplinary coverage in education and computing. The databases selected included ERIC, IEEE Xplore, EBSCO, Scopus, Google Scholar, and ProQuest. A set of relevant keywords was identified based on the study focus, and various combinations of these keywords were used in the search process. Keyword combination strategies were also applied to ensure the inclusion of studies related to AI integration in STEM education. The final search strings and keyword combinations are reported in Table 1.

Table 1

Designed search keywords

Search	Search keywords
Search #1	Artificial intelligence in education OR AI in teaching OR AI integration in classrooms OR AI-based instruction OR educational AI tools OR AI-supported pedagogy OR AI for teachers OR AI in school education OR AI use in K–12 classrooms OR AI use in elementary classrooms OR AI use in secondary classrooms
Search #2	AI in STEM education OR AI integration in STEM teaching OR using AI in STEM classrooms OR educational AI in STEM pedagogy OR combining AI and STEM education OR AI-supported STEM teaching OR STEM teachers using AI OR STEM educators’ perception on AI OR STEM educators' adoption of AI
Search #3	Barriers to AI use in STEM teaching OR challenges in AI-STEM integration OR teacher resistance to AI in STEM OR infrastructure challenges in STEM AI use OR privacy concerns in educational AI OR facilitators of AI integration in STEM OR enabling factors for AI in STEM classrooms OR opportunities for AI in STEM teaching OR benefits of AI for STEM instruction OR pedagogical advantages of AI in STEM
Search #4	1 AND 2 AND 3

Screening and Selection Process

As illustrated in Figure 1, the selection process followed the PRISMA guideline (Page et al., 2021). All identified records were imported into Zotero for reference management and duplicate removal, and uploaded to Covidence, online systematic review software (www.covidence.org), for screening and selection. In the screening phase, studies were first screened by title and abstract and then assessed in full text based on the predefined inclusion and exclusion criteria. The inclusion and exclusion criteria were developed in alignment with the research goals and applied throughout the review process. Eligible studies met the following criteria: (1) focus on artificial intelligence in education rather than general digital technologies; (2) involve STEM teachers, either pre-service or in-service, working in K–12 school settings; (3) report empirical findings (direct or synthesized) on teacher experiences, competencies, or practices; and (4) be published between 2018 and 2025 as peer-reviewed journal articles or full conference papers in English. Studies that failed to meet one or more of these criteria, including those conducted in higher education or non-school contexts, focused on non-STEM educators, lacked empirical evidence, or were not peer-reviewed, were excluded during the full-text screening stage.

As displayed in Figure 1, the initial database search identified 630 records. After removing 66 duplicate records, 564 records remained for title and abstract screening, of which 409 were excluded based on predefined inclusion and exclusion criteria. Among the studies reviewed for full-text review, 147 articles were assessed, and ultimately, 38 studies met all eligibility criteria and were included in the final systematic review. Descriptive statistics of the 38 reviewed studies show that most studies employed quantitative (n = 12; 32%) and qualitative (n = 10; 26%) designs, followed by mixed-methods (n = 8; 21%) and systematic review (n = 8; 21%). Regarding participant groups, statistics show that the majority of studies focused on STEM teachers in general (n = 13; 34%), followed by mathematics teachers (n = 11; 29%) and science teachers (n = 7; 18%).

Inter-Rater Reliability

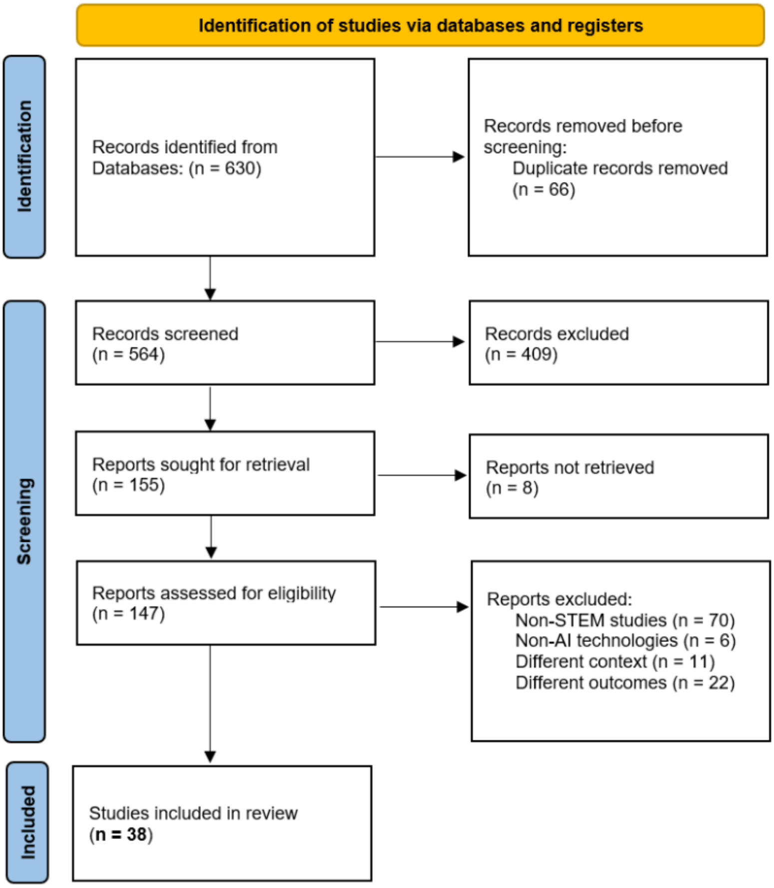
We used Cohen's kappa (k) to assess inter-rater reliability, as it measures reviewer agreement beyond chance (McHugh, 2012). Two reviewers independently screened all records at the title and abstract level (n = 564), achieving substantial agreement (Cohen's k = 0.81), which, based on McHugh's (2012) guidelines, indicates a high level of consistency between reviewers. Disagreements were resolved through structured discussion, with reviewers revisiting the inclusion and exclusion criteria to refine shared interpretations until consensus was reached.

Analysis and Coding Process

Following full-text screening, a structured data extraction and deductive coding process was conducted to support systematic organization and interpretation of the data. The deductive coding approach was employed because the AI-TPACK framework guided the analysis. At the first step, two reviewers organized all extracted findings into three analytical categories aligned with the research questions: facilitators of AI integration, barriers to AI integration, and ethical considerations related to AI use in K–12 STEM education.

Figure 2

PRISMA flow diagram



Two reviewers independently coded the data and compared coding decisions to identify discrepancies. In this stage, disagreements were resolved through iterative discussions focused on clarifying code definitions, resolving overlaps between categories, and refining theme boundaries. These discussions led to continuous revisions of the codebook to improve clarity and consistency.

At the second step, each category was examined through the dimensions of the AI-TPACK framework. In other words, facilitators, barriers, and ethical considerations were coded according to their relation to Technological Knowledge (AI-TK), Technological Pedagogical Knowledge (AI-TPK), Technological Content Knowledge (AI-TCK), and AI-Technological Pedagogical Content Knowledge (AI-TPACK). As deductive strategies are claimed to support conceptual coherence and analytical transparency (Bingham, 2023), the findings are grounded in AI-TPACK theory and demonstrate a structured, comparable pattern of facilitators, barriers, and ethical considerations across studies.

RESULTS

After analyzing 38 studies, the results addressing research questions were organized into subcategories representing facilitators, barriers, and ethical considerations related to AI-assisted STEM education in K-12 classrooms. It should be noted that some facilitators and barriers span multiple knowledge domains but are classified according to their predominant alignment with the domain most closely related to their core function.

Core Facilitators of AI Integration in STEM Education

AI-TK-Aligned Facilitators

In the AI-TK domain, the review revealed several key facilitators. At the initial step of AI integration, it is important to acknowledge that growing teachers' familiarity with AI tools like ChatGPT and Sphero robots will strengthen their ability to incorporate these tools into their teaching (Adeyele and Ramnarain, 2024; Kornyo, 2021; Cheah et al., 2025; Pörn et al., 2024). Teachers with digital skills have a solid foundation for adopting AI, as evidenced by "teachers surveyed have broad experience with digital tools and will likely become early adopters of AI tools in the classroom" (Pörn et al., 2024, p.70). AI literacy, a subcomponent of AI-TK, comprises the set of skills for evaluating AI-generated content and aligning it with learning objectives (Lin et al., 2025; Trung et al., 2025). Aktulun et al. (2024) stated that pre-service mathematics teachers also demonstrate confidence and curiosity in using AI for tasks like prompt engineering and personalized instruction, which are part of AI literacy. Using AI tools appears to stimulate teachers' interest, creative thinking, and questioning behaviors, which are closely associated with curiosity in instructional practice, as shown in "The participants recognized the added value of working with ChatGPT and expressed interest in using it in the future." (Segal and Biton, 2024, p. 1576). Professional development programs focused on teachers' AI-TK competencies, such as prompt writing and AI-generated content evaluation, have helped many teachers become more confident and prepared for AI-supported teaching (Alshorman, 2024; Biton and Segal, 2025). Professional development programs focused on teachers' AI-TK competencies, such as prompt writing and AI-generated content evaluation, have helped many teachers become more confident and prepared for AI-supported teaching (Alshorman, 2024; Biton and Segal, 2025).

AI-TCK-Aligned Facilitators

The review showed that AI tools can support STEM education by integrating technology with core content, helping teachers better understand subject matter, and aligning instruction with curriculum goals, thereby strengthening their subject-matter expertise (Trung et al., 2025). Some AI tools, such as ChatGPT and Dynamic Geometry Software (e.g., GeoGebra), can enhance content delivery by linking technology to representations of mathematical and STEM concepts (Biton & Segal, 2025, p. 218), improving precision and clarifying complex ideas and real-world applicability (Mohamed et al., 2022; Yanar and Ergene, 2025). As one study pointed out, "AI teaching tools might augment concept representation, facilitate procedural skill development, enhance problem-solving scaffolding…" (Lin et al., 2025, p.4).

Teachers also use AI to anticipate possible student responses and misconceptions. Yanar and Ergene (2025) demonstrated through a case study how a preservice mathematics teacher used AI chatbots to identify common misconceptions in a geometric topic. This capability helps teachers design lesson plans and highlight learning opportunities through potential students' misconceptions. In addition to AI STEM-related capabilities, AI enables teachers to generate accurate math problems and design instructional materials. Biton and Segal (2025) noted that "GenAI can explain and visualize various geometrical and algebraic concepts and theorems. ChatGPT can carry out interactive problem-solving 'dialogues' with the teachers to brainstorm and design step-by-step problems" (Biton and Segal, 2025, p. 204).

AI-TPK-Aligned Facilitators

In the field of AI-TPK, the review found that AI tools have significant potential to support teachers' pedagogical practices through technology integration (Biton & Segal, 2025). Teachers incorporate AI into their teaching practices, specifically in lesson planning and classroom management, with a focus on time-saving (Hammoud, 2025). Another AI facilitator involves generating customized exercises and individual learning paths as chemistry and mathematics-specific tasks (Hammoud, 2025; Pörn et al., 2024) to promote and facilitate personalized and data-driven learning in STEM classrooms (Garcia et al., 2025; Hammoud, 2025; McDaniel, 2025; Nuangchalerm, 2023; Pratiwi et al., 2025). Additionally, they use generative AI tools such as ChatGPT and robotics systems like Sphero to support the development of engaging instructional materials and adopt innovative teaching methods, including student-centered and adaptive learning, project-based learning, and improving instructional design (Adeyele & Ramnarain, 2024; Hammoud, 2025; Pratiwi et al., 2025; Price and Grover, 2025). Kornyo (2021) examined the impact of Sphero as an Artificial Intelligence Systems (AIS) and stated, "AIS promotes creativity through activity systems exemplified in STEM classrooms" (p. 120). One science teacher noted "ChatGPT... contributes... in generating thought-provoking questions that encourage student thinking and active participation..." (Adeyele & Ramnarain, 2024, p.210). Furthermore, AI enables constructivist approaches such as collaborative learning and real-world problem-solving by fostering critical thinking, project-based learning, and inquiry-based learning (Adeyele & Ramnarain, 2024; Kavitha & Joshith, 2024). Teachers also use AI to create interactive activities, differentiate instruction, and enhance motivation and engagement (Pratiwi et al., 2025), as evidenced by the statement: "I motivate students by designing interactive activities with specific goals, such as games and simulations" (Alissa & Hamadneh, 2023, p.1603). AI additionally helps facilitate adaptive pedagogical practices like personalized feedback and assessment design (Pörn et al., 2024), as shown by the statement: "Teachers may use AI tools to evaluate student learning, creating quizzes, voice-enabled assessments, and customized rubrics" (Alexandrowicz, 2024, p.348).

AI adoption also encourages the development of new competencies and motivates teachers to reconsider their pedagogical approaches (Hammoud, 2025). By increasing teachers' AI literacy, they engage with AI tools and learn to design AI-supported lessons, generate adaptive questions, and provide timely, personalized feedback, thereby transforming instructional decision-making beyond traditional teaching routines and shifting to AI-driven teaching practices.

AI-TPACK-Aligned Facilitators

The review demonstrates that AI integration supports interdisciplinary and student-centered STEM instruction when technological, pedagogical, and content knowledge are aligned rather than applied in isolation. Across studies, AI tools were not simply used for content delivery but for restructuring how content is represented, explored, and practiced. One study highlighted "Teachers with strong TPACK use technology to promote inquiry-based activities… and use a variety of representations… to assist students' development of content knowledge" (Biton & Segal, 2025, p. 205). These affordances make learning more adaptive and student-centered, where AI serves as a personalized support system rather than a static information source (Pörn et al., 2024).

Furthermore, evidence across studies suggests that the integration of AI tools such as ChatGPT reshapes instructional processes by enabling more interactive and responsive learning environments. AI tools not only support content delivery but also provide personalized feedback, adaptive learning pathways, and opportunities for collaborative engagement among students (Luzano, 2024; Magat & Sangalang, 2024). For example, ChatGPT has been shown to "provide personalized feedback" and support "adaptive learning methodologies," allowing teachers to tailor instruction to students' needs (Trung et al., 2025, p. 73).

This shift, however, depends heavily on teachers' technological and pedagogical readiness. Without sufficient training, AI tools are often used at a surface level, which limits their instructional potential. Accordingly, studies highlight the need for both technical and pedagogical preparation to support meaningful AI integration in classroom practice (Magat & Sangalang, 2024). With structured professional development, teachers are more likely to use AI as an instructional partner, supporting lesson planning, assessment, and student interaction as part of their teaching practice. Table 2 summarizes the core facilitators across AI-TPACK domains.

Table 2

Core Facilitators of AI Integration in STEM Education

Domains	Sub-categories	Sample research
AI-TK	Digital skill foundations for AI use; Teacher curiosity in using AI; Professional development programs on teachers' AI-TK competencies.	Adeyele & Ramnarain (2024); Aktulun et al. (2024); Alshorman (2024); Biton & Segal (2025); Cheah et al. (2025); Kornyo (2021); Lin et al. (2025); Pörn et al. (2024); Segal & Biton (2024); Trung et al. (2025)
AI-TCK	AI-supported representation of STEM concepts; STEM content visualization and procedural fluency; AI-assisted real-world modeling, coding, and problem generation; Diagnosis of student misconceptions; Generation of content-specific tasks.	Biton & Segal (2025); Lin et al. (2025); Mohamed et al. (2022); Pörn et al. (2024); Trung et al. (2025); Yanar & Ergene (2025)

AI-TPK	AI-supported lesson planning and instructional design; Inquiry-based and project-based learning enabled by AI; Student-centered and constructivist pedagogical approaches; Design of interactive learning activities and simulations; Differentiated instruction and adaptive pedagogical support; AI-enabled feedback, assessment, and evaluation practices.	Adeyele & Ramnarain (2024); Alexandrowicz (2024); Alissa & Hamadneh (2023); Biton & Segal (2025); Garcia et al., 2025; Hammoud, 2025; Kavitha & Joshith (2024); Kornyo (2021); McDaniel, 2025; Nuangchalerm, 2023; Pörn et al. (2024); Pratiwi et al., 2025; Price & Grover (2025)
AI-TPACK	Interdisciplinary AI-integrated curriculum design; Pedagogically guided AI-supported knowledge delivery; AI-Supported collaborative learning environments; Teacher professional development for AI-TPACK competencies.	Almusaed et al. (2024); Kornyo (2021); Li & Manzari (2025); Luzano (2024); Magat & Sangalang (2024); Trung et al. (2025)

Significant Barriers to AI Integration in STEM Education

AI-TK-Aligned Barriers

The systematic review indicates that significant technology-related barriers include insufficient infrastructure, from limited access to devices and reliable internet connectivity, to a lack of direct experience with AI tools and guidance on their instructional use. It means that technological inadequacies in school infrastructure and limited school resources impede teachers' ability to implement AI (Lintner, 2024; Pratiwi et al., 2025; Yalcin et al., 2024). As illustrated by one teacher: "I cannot use one hundred percent integration in class because the technology in our school is not sufficient in this regard" (Yalcin et al., 2024, p. 355). The rapid growth of AI tools without clear instructional guidance increases cognitive load and reduces teachers' confidence in selecting and implementing appropriate technologies (Hammoud, 2025; Lintner, 2024). Moreover, ambiguity in AI tools' functions reduces teachers' perceived ease of use, consequently, making them more challenging to navigate and integrate (AlKanaan, 2022).

From the teacher side, obstacles to AI integration are not only rooted in infrastructure and access but also stem from insufficient training in AI and its educational applications (Garcia et al., 2025). Sangalang (2024) pointed out that misconceptions about AI, such as perceiving it as autonomous robots, undermine teacher trust and willingness to adopt AI in mathematics education.

AI-TCK-Aligned Barriers

Alongside technological challenges, the review identifies a set of barriers embedded within the technological STEM context. These barriers include limited teacher competencies in working with AI-generated data and interpreting models and algorithmic outputs (Al Darayseh & Mersin, 2025; López-Costa et al., 2025). This limitation is closely related to the technical complexity of algorithms and the human-AI interaction methods in many STEM-oriented AI tools (Hammoud, 2025). For example, Ajayi (2024) notes that while AI-based systems such as GradeScope, which assess mathematics and engineering assignments, can support instructional processes in STEM, their use often involves navigating complex problem-solving structures.

Furthermore, several studies raise concerns that STEM educators may use AI tools excessively, which results in reducing learning opportunities for students to actively engage in critical thinking, computational reasoning, and problem-solving processes (Kavitha & Joshith, 2024; Leon et al., 2025). Such overreliance on AI risks shifting learning away from cognitive effort toward AI-generated outputs, particularly when AI tools do not support disciplinary learning goals.

AI-TPK-Aligned Barriers

The review indicates that barriers associated with the technological pedagogical knowledge domain are primarily rooted in the misalignment of AI tools with instructional strategies and curriculum goals. When AI technologies integrate into curricula without curriculum revision, it results in a mismatch between established curriculum standards and emerging AI-enabled instructional practices (Ajayi, 2024; Cheah et al., 2025; García et al., 2025; Kavitha & Joshith, 2024; McDaniel, 2025), as García et al. (2025) emphasized that "a critical factor in AI integration is the design of curriculum and pedagogy that align with the demands of an AI-driven world" (p. 26).

Additional challenges include risks of diminished instructional control and the potential marginalization of teachers' professional roles. There is concern that AI tools may replace teachers' authentic roles rather than serve as cognitive partners (Hammoud, 2025; Leon et al., 2025). Another threat that magnifies the replacement of teachers is students' overreliance on AI, which leads to blind trust in AI-generated outputs (Pörn et al., 2024). It is more observed among students with lower levels of motivation and literacy (de Putter-Smits et al., 2025; Pratiwi et al., 2025).

Another persistent challenge to using AI technology is teachers' dissatisfaction with the available professional development, which leads to insufficient teacher readiness (Pratiwi et al., 2025) and, consequently, pedagogical hesitation and uncertainty in decision-making. These findings support this claim that, despite teachers' tendency to use AI, insufficient training and unclear integration strategies hinder its effective pedagogical use (Ajayi, 2024; Cheah et al., 2025).

AI-TPACK-Aligned Barriers

The findings of the systematic review show that many STEM teachers struggle to consistently apply AI tools across different science topics, with low self-efficacy and low confidence about when and how AI should be used in classrooms (Viberg et al.,2025; Wang & Chen, 2024). The core barriers across AI-TPACK domains are presented in Table 3.

Table 3

Significant Barriers to AI Integration in STEM Education

Domains	Sub-categories	Sample research
AI-TK	Limited access to AI tools and insufficient infrastructure; Lack of technical guidance for instructional use; Ambiguity in AI tools' functions; Low perceived ease of use of AI tools.	AlKanaan (2022); Hammoud (2025); García et al (2025); Lintner (2024); Sangalang (2024); Yalcin et al. (2024)
AI-TCK	Limited ability to interpret AI-generated data and models; Difficulty of interpreting algorithmic outputs; High technical complexity of STEM-oriented AI tools; Overreliance on AI undermining core STEM practices.	Al Darayseh & Mersin (2025); Hammoud (2025); Kavitha & Joshith (2024); León et al. (2025); López-Costa et al. (2025)
AI-TPK	Misalignment between AI tools and curriculum goals; Reduced instructional control and teacher role marginalization; Increased student overdependence on AI; Pedagogical hesitation and uncertainty.	Cheah et al. (2025); de Putter-Smits et al. (2025); García et al. (2025); Hammoud (2025); Kavitha & Joshith (2024); Pratiwi et al. (2025); Pörn et al. (2024)

AI-TPACK	Low teacher self-efficacy in applying AI across STEM topics; Lack of integrated AI-TPACK focused professional development.	AlKanaan (2022); García et al. (2025); Li & Manzari (2025) Viberg et al. (2025); Wang & Chen (2024)

AI Ethics in STEM Education

Based on the AI-TPACK framework, ethical considerations intersect with all domains rather than belonging to a single, discrete category. This overlap indicates that ethical issues cannot be isolated within one domain; instead, they permeate the technological, pedagogical, and content-related dimensions of AI integration. Therefore, the ethical considerations identified across the reviewed studies function holistically, influencing and shaping practices across the entire framework. The systematic review identifies multiple ethical considerations associated with the use of AI in STEM education. The findings reveal that ethical issues are not treated as peripheral concerns; rather, they are positioned as central conditions influencing the responsible integration of AI in STEM classroom practice. Concerns related to student data privacy and information security are prominently reported across studies. STEM teachers expressed uncertainty about how AI systems sort and protect student data, especially when using it to personalize learning. Since it relies on the continuous collection, analysis, and storage of detailed student data, including learning behaviors, performance patterns, and, at times, sensitive personal information. Questions regarding whether existing institutional safeguards are sufficient to protect sensitive student information remain contested in the literature (Ajayi, 2024; Hammoud, 2025; Nuangchalerm, 2023). As Nuangchalerm (2023) emphasizes, when AI is used to personalize STEM learning experiences, "to safeguard sensitive student information from being compromised or misused, educational institutions have a responsibility to ensure that effective data privacy protections are in place" (p. 82).

Given the importance of data privacy, educators emphasized the urgent need for policy development and transparency regarding the ethical and moral implementation of AI. De Putter-Smits et al. (2025) noted, "All (teachers) expressed a clear need for policy development to specify what applications of GenAI are permitted in what circumstances, and how to report the use of GenAI" (p.7). There was broad agreement that educational policy should remain context-sensitive, flexible, and open to negotiation between teachers and learners. There is an obvious need for clear policies that explain the undermining of generative AI risk implementation (De Putter-Smits et al., 2025). Another important aspect of ethical AI implementation, apart from the demand for transparent guidelines, is the need for ethical character development among students, including academic honesty (Wright, 2025). Educators and curriculum designers must consider and provide the necessary content and learning environment to help students acquire these essential skills and competencies. This set of training is unavoidable not just because it ensures students use AI ethically, but more importantly, to prevent their learning from being hindered by the misuse of this tool, such as “plagiarism and superficial engagement with content” (De Putter-Smits et al., 2025). This is an example of blind trust, leading to less cognitive engagement with the content generation process, which prevents learning from thinking and deepening, causing it to stay at a basic and superficial level (Ajayi, 2024). Table 4 summarizes the key ethical considerations identified across the reviewed studies in K–12 STEM education. Although these issues are reported as they emerge within STEM contexts, they may reflect ethical considerations associated with AI integration in educational settings more generally.

Table 4

Ethical Considerations of AI Integration in STEM Education

Domains	Sub-categories of AI Ethics	Sample research
AI Ethics	Data privacy and student data protection; Algorithmic bias and equity concerns; Transparency in AI data collection, storage, and use; Policy development for ethical and responsible AI use; Context-sensitive and negotiable AI governance.	Ajayi (2024); Al Darayseh & Mersin (2025); de Putter-Smits et al. (2025); Hammoud (2025); Karakose & Tülübas (2023); Lintner (2024); Nazaretsky et al. (2022); Nuangchalerm (2023); Riggs (2025); Sangalang (2024); Wright (2025)

DISCUSSION

In modern STEM education, artificial intelligence has been introduced as a transformative innovation with the potential to advance K-12 teaching and learning methods. Nevertheless, AI-STEM literature indicates that AI integration in K-12 is profoundly influenced by technological infrastructure and expertise, pedagogical practices, STEM discipline-specific concepts, and ethical boundaries. Through the lens of the AI-TPACK framework, these interactions reveal a landscape of AI integration that is both promising and limiting.

The findings of this systematic review highlight the growing capacity of AI tools to support both conceptual and procedural understanding of STEM concepts through constructivist teaching approaches. AI facilitates this process by generating multiple representations, enabling adaptive feedback, supporting iterative problem-solving, and scaffolding inquiry-based learning. This suggests that GenAI should not be viewed merely as a technological tool; rather, when thoughtfully integrated based on its capabilities and instructional context, it can function as a co-assistant in the teaching process. From a practical standpoint, this reconceptualization of the AI role requires teachers to make informed decisions about when and how to integrate AI tools. As a result, effective AI integration involves not only access to tools but also the development of implementation knowledge through structured, ongoing training aligned with the AI-TPACK framework domains.

However, these opportunities are hindered by structural, pedagogical, and epistemic barriers. Beyond infrastructure gaps and limited technical skills, the rapid deployment of AI tools without clear pedagogical guidance introduces uncertainty regarding their effective integration. This uncertainty often translates into practical challenges, as teachers question the instructional value of AI due to weak alignment with pedagogical strategies and low confidence in their decision-making. These issues largely stem from limited AI literacy, which is further exacerbated by inconsistent professional development efforts. In addition to the mentioned challenges, there are growing concerns in STEM disciplines that excessive reliance on AI may weaken students' critical, mathematical, and computational reasoning skills. This risk underscores the importance of professional development that strengthens teachers' AI literacy and supports the adaptive transformation of their instructional practices in response to emerging technologies. The findings highlight a clear need for coherent and comprehensive professional development programs (Ajayi, 2024; AlKanaan, 2022; Chu, 2025; Garcia et al., 2025; Li & Manzari, 2025). While structured, practice-based training has been shown to enhance instructional practices, many of the identified barriers stem from its absence. Without targeted support, teachers often experience a disconnect between their instructional intentions and AI-generated outputs, which can lead to misconceptions about AI's role in teaching and learning or to its uncritical or unethical use.

The ethical findings also reveal that teachers face ongoing tensions when using AI in STEM classrooms. For example, AI can support personalized learning, but it depends on collecting and analyzing large amounts of student data. This creates concerns about privacy and student data protection. These tensions suggest that ethical AI integration cannot be addressed just through policy or technical safeguards. Instead, they highlight the need for a more nuanced approach to professional development that prepares teachers to make ethical decisions in context. Therefore, as teachers better understand how AI works and the risks involved, they become more aware of the consequences of their instructional choices. Within the modified AI-TPACK framework, this suggests that ethical awareness should be embedded in AI literacy, shaping how teachers apply technological, pedagogical, and content knowledge in context. Accordingly, professional development initiatives should move beyond short-term workshops and tool-focused tutorials. Rather than treating AI as a set of isolated technical skills (AI-TK), effective professional learning should support teachers in integrating AI with disciplinary content knowledge (AI-TCK) and aligning its use with pedagogical goals and instructional decision-making (AI-TPK). From this perspective, meaningful professional development involves cultivating competencies across all AI-TPACK domains in an integrated manner, rather than addressing them separately. Ethical considerations should be embedded as a core component of AI literacy and technological knowledge, as reflected in the modified AI-TPACK framework (Figure 1), rather than treated as a peripheral concern. Such programs should promote sustained AI readiness by enabling teachers to engage with AI critically, ethically, and intentionally. This is supported by the review's findings, which indicate that teachers with stronger AI understanding are more likely to recognize and address issues such as data privacy, algorithmic bias, transparency, and student safety. Lastly, to achieve the goal of effective AI integration, collaboration among all stakeholders, including teacher education programs, school leaders, curriculum designers, policymakers, and technology developers, comes to the foreground (Nuangchalerm, 2023). Such collaboration ensures professional learning opportunities are coherent, context-responsive, and aligned with curriculum standards and classroom realities.

Taken together, the findings of this review suggest several core principles for designing professional development that support effective AI integration in K–12 STEM education. Professional development should move beyond fragmented, tool-centered approaches commonly found in AI–STEM literature. Instead, it should support teachers in developing a comprehensive understanding of AI as an evolving sociotechnical system, including its interaction with human decision-making and instructional contexts. Ethical considerations should also be embedded as a subcomponent of technological competencies, rather than treated as a separate domain. When AI integration is approached as isolated tool adoption without coherent pedagogical and disciplinary grounding, it often results in confusion, limited effectiveness, and superficial classroom use. In contrast, this review conceptualizes sustainable AI integration as the coordinated development and alignment of pedagogical, technological, disciplinary, and ethical competencies, as articulated in the AI-TPACK framework.

Furthermore, the findings are influenced by contextual factors such as national policies, socioeconomic conditions, infrastructure, and staff capacity. It means AI has the potential to both reduce and fuel existing educational inequalities. Given that the AI-TPACK framework is inherently context-sensitive, these results underscore the need for more context-responsive approaches to professional development in AI integration.

CONCLUSION

This systematic review synthesized 38 empirical studies to examine facilitators, barriers, and ethical considerations influencing AI integration in K–12 STEM education through the AI-TPACK framework. The findings show that AI integration is enabled by a range of facilitators, including STEM content visualization and procedural fluency, the diagnosis of student misconceptions, the design of interactive learning activities and simulations, AI-enabled feedback, assessment and evaluation practices, and AI-supported collaborative learning environments. At the same time, these facilitators are often constrained by persistent barriers, including limited infrastructure, insufficient technical and pedagogical preparation, misalignment between AI tools and curriculum goals, and low teacher confidence in decision-making. Ethical concerns, particularly related to data privacy, algorithmic bias, transparency, and student overreliance on AI, emerge across studies as core issues in STEM classrooms, raising critical equity and accessibility challenges, as uneven access to AI tools and biased algorithmic systems may reinforce existing educational disparities.

This study contributes to the literature by reframing AI integration as a coordinated and competency-based process rather than an isolated tool adoption. By applying the AI-TPACK framework, the review demonstrates that effective AI use in STEM depends on the alignment of technological knowledge, disciplinary understanding, pedagogical decision-making, and ethical awareness. Notably, the findings highlight those fragmented approaches, in which AI is treated primarily as a technical skill (AI-TK) without strong connections to content (AI-TCK), pedagogy (AI-TPK), or ethics, which are key reasons why many integration efforts fail. In this way, the study advances current scholarship by showing that sustainable AI integration requires the co-development of multiple, interrelated competencies, with ethics embedded as a core element of AI literacy rather than a complementary guideline. These findings further suggest that AI-TPACK should be seen in context, which influences how AI-TPACK competencies are developed and enacted in practice.

Despite its contributions, this systematic review has several limitations that should be acknowledged. First, the analysis, based on a selected set of databases, was restricted to peer-reviewed studies published between 2018 and 2025, which may exclude emerging practices reported in the literature and practitioner-oriented publications. Second, although the included studies span diverse educational contexts, differences in AI policies, infrastructure, and teacher preparation systems limit the generalizability of the findings across all K–12 STEM settings. To address this limitation, future studies are advised to expand database coverage, include multilingual literature, and apply rigorous quality assessment criteria. Longitudinal and comparative studies are also needed to examine how contextual factors shape

AI integration and to explore theoretical frameworks that capture deeper shifts in teaching, learning, and ethical practice in STEM education. Given that AI integration is shaped by multiple actors and decision-making levels, it is recommended that future studies adopt multifaceted analytical perspectives by examining the experiences and attitudes of STEM educators, school leaders, curriculum designers, and AI–STEM technology developers in real-world classroom contexts. Ultimately, AI integration in K–12 STEM education depends not on technology alone, but on the aligned development of technological, pedagogical, content, and ethical competencies within context. Without systematic integration, AI may risk reinforcing existing inequities; however, when carefully and contextually integrated, it can support the meaningful transformation of STEM learning.

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