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Integrating Emerging Technologies into STEM Education: Effects on Student Engagement, Problem-Solving, and Learning Outcomes

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Abstract

Emerging technologies are reshaping STEM education by enabling interactive, adaptive, immersive, data-informed, and increasingly intelligent learning experiences. Yet the literature remains fragmented: artificial intelligence, augmented and virtual reality, educational robotics, digital games, learning analytics, adaptive learning, and smart learning environments are often examined as separate research streams, while engagement, problem-solving, and learning outcomes are frequently studied in isolation. This paper presents a structured integrative review to synthesize how emerging technologies contribute to student engagement, problem-solving, and STEM learning outcomes. The synthesis examines studies through dominant technology, learning mechanism, outcome emphasis, and implementation conditions. Five recurring mechanisms emerge: interactive learning and visualization, adaptive and personalized support, authentic problem-centered activity, immediate feedback and learner monitoring, and collaborative or self-regulated participation. Across the evidence, emerging technologies are generally associated with positive engagement and learning effects, but their effectiveness depends on pedagogical integration, teacher support, task design, technological affordances, and contextual conditions. Problem-solving appears particularly dependent on active and purposeful technology use rather than passive exposure. Based on the synthesis, the paper proposes the Emerging Technology–Engagement–Problem-Solving–Learning Outcomes Framework (E-TEPS), linking technology integration to learning through engagement and problem-solving while positioning pedagogical integration as a moderating condition. The framework provides a basis for future research and for designing STEM learning environments that prioritize meaningful cognitive activity, learner participation, and educational value over technology novelty.

1. Introduction

STEM education is increasingly moving beyond static digital content toward learning environments in which students can observe phenomena, simulate systems, collaborate around complex tasks, obtain immediate feedback, and revise solutions with support from intelligent or immersive technologies. This shift is driven by the growing availability of artificial intelligence (AI), augmented and virtual reality (AR/VR), educational robotics, digital games, learning analytics, adaptive learning systems, and connected learning environments. The educational significance of these technologies, however, is not determined by technological sophistication alone. Their value depends on how well technology is integrated with learning goals, instructional strategies, teacher support, and meaningful student activity (Leavy et al., 2023; Ouyang & Xu, 2024; Tene et al., 2024).

The emerging evidence base suggests that technology can support STEM learning in several ways. Immersive tools can make abstract or spatial concepts more visible and manipulable, robotics can support hands-on experimentation and computational thinking, games can increase motivation and persistence, and AI can provide adaptive explanations, feedback, and personalized support (Ibáñez-Espiga & Delgado-Kloos, 2018; Wang et al., 2022; Darmawansah et al., 2023; Almasri, 2024). Learning analytics and adaptive systems add a data layer through which learner progress can be monitored and instructional resources can be adjusted (Ifenthaler & Yau, 2020; Haider et al., 2024a).

Despite these advances, the literature remains fragmented. Studies frequently focus on one technology, such as VR, robotics, AI, or game-based learning, and evaluate one or two outcomes, such as motivation, achievement, or practical skill. Reviews of emerging technologies in STEAM and integrated STEM indicate that the field has expanded rapidly, but substantial variation remains in technologies, pedagogies, populations, intervention durations, and outcome measures (Leavy et al., 2023; Le et al., 2023). This fragmentation makes it difficult to explain the mechanism through which technology contributes to learning. In particular, student engagement and problem-solving are often discussed as outcomes rather than as connected processes that may explain improvements in STEM learning.

Problem-solving deserves special attention because it sits near the center of STEM practice. Authentic STEM tasks require learners to identify problems, represent systems, generate alternative solutions, test ideas, interpret evidence, and revise designs. Educational robotics and integrated STEM studies consistently emphasize active problem-oriented learning, whereas some technology comparison studies show that improvements in performance may not necessarily translate into deeper cognitive activity (McLure et al., 2022; Darmawansah et al., 2023; Lawson et al., 2024). This distinction suggests that a technology may be educationally useful not because students spend more time using it, but because it changes what students do cognitively and socially during learning.

The present paper therefore investigates emerging technologies through an integrative lens. It asks how technology integration relates to student engagement, how engagement and technology-supported activity relate to problem-solving, and how these processes contribute to STEM learning outcomes. The paper also emphasizes pedagogical integration as a condition that can strengthen or weaken these relationships. This perspective is consistent with evidence showing that instructor support, instructional strategy, technological affordances, intervention duration, and learner characteristics influence the effectiveness of educational technology (Ouyang & Xu, 2024; Tene et al., 2024).

The paper makes three contributions. First, it synthesizes evidence across multiple emerging-technology streams within a common STEM education framework. Second, it distinguishes student engagement and problem-solving as linked learning mechanisms rather than treating them as interchangeable outcomes. Third, it proposes the Emerging Technology–Engagement–Problem-Solving–Learning Outcomes Framework (E-TEPS), which integrates technology affordances with pedagogical conditions and learning processes. The remainder of the paper reviews the literature, explains the review method, presents the cross-study synthesis, develops the framework and propositions, discusses implications, and identifies priorities for future empirical research.

2. Literature Review

2.1 Emerging Technologies as a STEM Learning Infrastructure

Emerging technologies in STEM education should be understood as a set of learning affordances rather than as a single intervention. AI can process learner information and generate feedback, AR/VR can support visualization and simulation, robotics can connect programming to physical action, games can embed challenge and feedback in interactive environments, and analytics can provide continuous information about learner progress (Leavy et al., 2023; Wang et al., 2024). Smart and connected learning environments add infrastructure that links data, devices, instructional resources, and contextual information. Benita et al. (2021), for example, illustrate how an IoT-based STEM learning ecosystem can support data-driven thinking by connecting sensing, learning activities, and interpretation.

The literature also suggests that technology categories overlap. An intelligent STEM activity may combine sensors, analytics, AI, adaptive feedback, and immersive visualization. This convergence is important because learning effects may emerge from the interaction of several technologies rather than from any single tool (Haider et al., 2024b; Wang et al., 2024). A useful analytical distinction is therefore between the technology itself and the learning function that the technology enables. Across the reviewed literature, recurring functions include representation and visualization, personalization and adaptation, collaboration, experimentation, feedback, monitoring, and simulation.

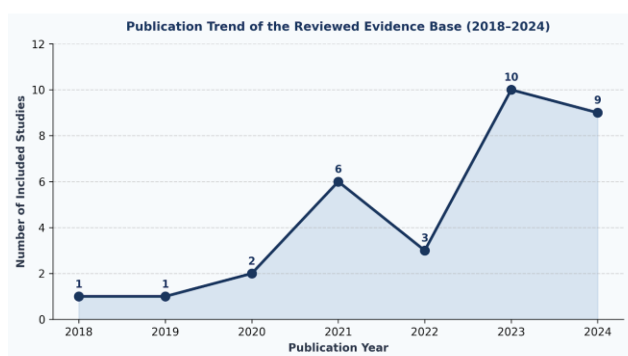

Figure 1:. Publication trend of the 32-study evidence base, 2018–2024. The chart shows the annual distribution of included studies and highlights the sharp growth in the evidence base after 2022.

Table 1. Emerging technologies and dominant STEM learning functions

Technology	Learning function	Outcomes
AI / GenAI	Personalization, explanation, feedback	Engagement; conceptual learning
AR / VR / XR	Visualization, simulation, spatial learning	Engagement; understanding; practical skills
Robotics	Hands-on design, programming, debugging	Problem-solving; STEM competence
Digital games	Challenge, repetition, immediate feedback	Engagement; motivation; achievement
Analytics / adaptive	Monitoring, prediction, adaptive pathways	Self-regulation; engagement; performance
IoT / smart environments	Connected sensing and contextual data	Data-driven thinking; personalization

2.2 Artificial Intelligence and Generative AI

AI has become one of the most prominent emerging technologies in education because it can support learner profiling, prediction, adaptive instruction, assessment, intelligent tutoring, and personalized feedback (Haider et al., 2021; Chiu et al., 2023; Wang et al., 2024). In science education, AI is increasingly discussed as a tool for explanation, content generation, assessment support, and learning personalization, although its educational value depends on accuracy, pedagogical alignment, and teacher oversight (Almasri, 2024).

Generative AI adds a new dimension because learners can interact with language models directly. Studies of ChatGPT in education identify opportunities for explanation, brainstorming, feedback, and assistance, but also highlight risks related to inaccurate information, over-reliance, academic integrity, and cognitive offloading (Cooper, 2023; Lo, 2023; Montenegro-Rueda et al., 2023). For STEM learning, the critical issue is therefore whether AI supports reasoning or substitutes for it. An AI system that simply supplies answers may increase short-term task completion without strengthening problem-solving, whereas an AI system that prompts learners to compare alternatives, explain reasoning, test assumptions, or reflect on errors can potentially deepen cognitive engagement.

The literature on AI adoption also shows that implementation is not purely a technical decision. Faculty readiness, perceived usefulness, trust, institutional support, and awareness of risks shape adoption and educational use (Haider et al., 2023). Accordingly, AI should be treated as one component of a broader pedagogical system rather than an independent cause of improved learning outcomes.

2.3 AR, VR, and Immersive Learning

AR, VR, and related immersive technologies are especially relevant to STEM when learners need to visualize objects, processes, systems, or environments that are difficult to observe directly. Systematic reviews show that AR can support STEM learning and spatial intelligence, while meta-analytic work indicates that VR can positively influence technical and practical skills (Ibáñez-Espiga & Delgado-Kloos, 2018; del Cerro Velázquez & Morales Méndez, 2021; Ma et al., 2022; Yang et al., 2024).

Immersive technologies can also strengthen engagement because they increase perceptual richness, interaction, and the sense of being present within a simulated environment. Tene et al. (2024) found that most of the STEM studies in their review reported positive effects on engagement and/or performance. Yet Lawson et al. (2024) caution that media-comparison studies may confound the effect of VR with the effect of instructional design. This is an important methodological lesson: the educational effect may come from the combination of immersion, active task design, feedback, and novelty rather than from VR alone.

2.4 Educational Robotics and Hands-On Problem-Solving

Educational robotics connects abstract computational ideas to physical action. Students can program, build, test, observe system behavior, diagnose failures, and iterate on designs. Reviews of robotics-based STEM education identify interdisciplinary learning, computational thinking, design practices, and problem-solving as recurring educational objectives (Darmawansah et al., 2023). The multilevel meta-analysis by Ouyang and Xu (2024) further indicates that robotics can support STEM learning, while the effectiveness of robotics varies with instructional strategy, teacher support, intervention duration, and robotics type.

Robotics therefore provides a particularly useful example of why problem-solving should be distinguished from achievement. A robotics task may improve conceptual knowledge while simultaneously requiring students to engage in iterative debugging and solution evaluation. Such activity creates an observable link between engagement and problem-solving that is less visible in technology uses centered on passive content consumption. Trapero-González et al. (2024) similarly emphasize the relevance of educational robotics to STEM competence in primary education.

2.5 Digital Game-Based Learning

Digital game-based learning uses challenge, rules, goals, feedback, and interaction to structure learning activity. Meta-analytic evidence indicates that digital games can produce positive STEM achievement effects, while game-design features can further influence learning (Wang et al., 2022; Gui et al., 2023). Games are especially relevant to engagement because they can encourage persistence, repeated practice, and immediate feedback. However, effective STEM game design must still connect challenge mechanics to disciplinary reasoning rather than simply adding points or rewards to existing content.

2.6 Learning Analytics, Adaptive Learning, and Smart Environments

Learning analytics and adaptive systems provide the data and decision layer of emerging technology integration. Systematic reviews show that analytics can support monitoring, prediction, feedback, and intervention, although changes in behavior do not necessarily guarantee improved final performance (Ifenthaler & Yau, 2020; de Sousa et al., 2021). Adaptive learning extends this logic by changing content, sequence, assessment, or feedback based on estimated learner needs. The effectiveness of adaptive platforms therefore depends on whether adaptation is timely, relevant, interpretable, and connected to meaningful learning activity (Haider et al., 2024a).

Smart learning environments combine these functions with connected devices, learner data, and contextual information. Benita et al. (2021) show how an IoT-enabled learning ecosystem can support data-driven STEM learning, while Haider et al. (2024b) emphasize the role of connected sensors and personalization. The key synthesis is that data collection is only educationally meaningful when it changes a learning decision. Monitoring without pedagogical response may increase visibility without improving learning.

2.7 Student Engagement as a Learning Mechanism

Student engagement should be understood as multidimensional. Behavioral engagement includes participation and persistence; emotional engagement includes interest and enjoyment; cognitive engagement involves mental effort and strategy use; and agentic engagement can include students' contributions to shaping their learning experience. Educational technology research has frequently examined engagement, but measures differ considerably across studies (Bond et al., 2020).

Emerging technologies can influence engagement by increasing interaction, relevance, feedback, personalization, and perceived usefulness. Online learning research also shows that technology access and digital equity shape whether students can participate effectively (Haider et al., 2021). Thus, the engagement pathway is not simply technology exposure → motivation. It is more plausibly technology affordance → meaningful activity → perceived relevance and agency → sustained engagement.

2.8 Problem-Solving as a Cognitive Mechanism

Problem-solving is central to STEM because it requires learners to apply knowledge in situations where the solution is not immediately given. Integrated STEM research consistently emphasizes authentic, interdisciplinary tasks, while robotics research highlights iterative design and debugging (McLure et al., 2022; Le et al., 2023; Darmawansah et al., 2023). Emerging technologies can support problem-solving when they help learners represent problems, explore alternatives, simulate consequences, receive feedback, and revise solutions.

However, problem-solving can be weakened when technology reduces the cognitive work that learners need to perform. This concern is particularly relevant to generative AI. Cooper (2023) and Lo (2023) show both useful and problematic possibilities of ChatGPT, while the broader AI literature calls for pedagogical designs that preserve learner reasoning and instructor oversight (Chiu et al., 2023; Almasri, 2024). The relevant question is therefore not whether technology solves the problem, but whether technology helps students become better problem solvers.

2.9 STEM Learning Outcomes

The reviewed literature uses multiple indicators of learning outcomes, including achievement, conceptual understanding, practical skills, STEM competence, retention, and self-reported learning. Meta-analyses of games, VR, and robotics generally report positive effects, but the magnitude varies across contexts and outcome types (Wang et al., 2022; Ma et al., 2022; Ouyang & Xu, 2024; Yang et al., 2024). This variation reinforces the value of distinguishing proximal learning processes, such as engagement and problem-solving, from more distal outcomes such as achievement.

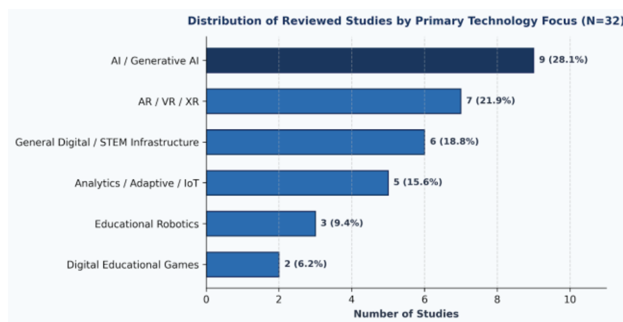

Figure 2. Distribution of reviewed studies by primary technology focus. The bars summarize the dominant technology category assigned to each of the 32 included studies; categories reflect the primary emphasis used for cross-study synthesis. Source: authors' thematic coding.

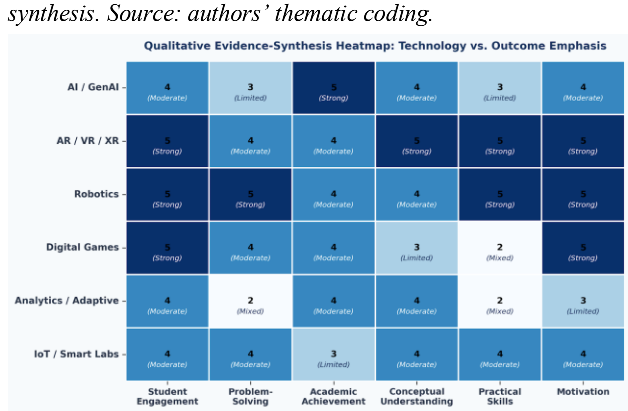

Figure 3. Qualitative evidence-synthesis heatmap of technology and outcome emphasis. Cell values represent author-coded qualitative evidence strength/centrality in the reviewed literature and are not pooled effect sizes or statistical estimates.

Table 2: Comparative evidence profile across technology streams

Technology	Evidence profile	Key condition
AI / GenAI	Positive but mixed across uses	Teacher oversight; reasoning-oriented tasks; accuracy
AR / VR / XR	Generally positive for engagement and skills	Active task design; immersion–task fit
Robotics	Strong alignment with STEM problem-solving	Teacher support; duration; instructional strategy
Digital games	Positive engagement and achievement effects	Game mechanics aligned with STEM goals
Analytics / adaptive	Positive but variable learning effects	Actionable feedback; meaningful adaptation
IoT / smart environments	Promising, context-dependent	Connected data translated into learning decisions

3. Review Method

This study uses a structured integrative literature-review design. The purpose is to synthesize mechanisms across multiple emerging-technology streams rather than calculate a pooled meta-analytic effect. The evidence base consists of 32 open-access studies published from 2018 through 2024. The set includes the 32 references specified for this manuscript, covering peer-reviewed research, systematic reviews, meta-analyses, and selected US Journal of New Insights in Tech & Education studies directly relevant to the topic.

The review followed four stages: (1) scope and relevance screening; (2) extraction of technology focus, educational mechanism, outcome emphasis, and implementation condition; (3) thematic coding; and (4) cross-study synthesis into research gaps and a conceptual framework. Studies were grouped by dominant technology focus even when individual studies addressed multiple technologies. Outcome emphasis was coded across engagement, problem-solving, and learning outcomes, with additional attention to motivation, practical skills, personalization, equity, and governance.

The review gives greater interpretive weight to systematic reviews, meta-analyses, and empirical studies that report or explain an educational mechanism. Conceptual or review studies are used to define constructs and identify recurring themes. The figures in this paper are therefore synthesis aids, not new empirical estimates. In particular, the qualitative evidence-emphasis matrix is an author coding device intended to visualize where the literature is concentrated; it should not be interpreted as an effect-size estimate.

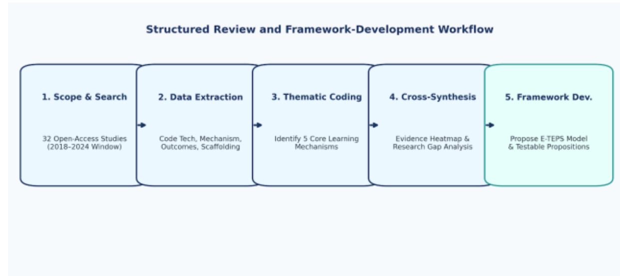

Figure 4. Structured review and framework-development workflow. The process moves from scope and search through data extraction, thematic coding, cross-study synthesis, and development of the E-TEPS framework.

4. Findings and Cross-Study Synthesis

4.1 Evidence Distribution

Table 3: Cross-study mechanisms linking technology to STEM learning

Mechanism	Learning contribution	Representative evidence
Activity change	Simulation, debugging, adaptive paths, interactive explanation	Ma et al. (2022); Ouyang & Xu (2024)
Engagement	Relevance, challenge, feedback, visible progress	Bond et al. (2020); Wang et al. (2022); Tene et al. (2024)
Problem-solving	Modeling, testing, evaluating, revising	McLure et al. (2022); Darmawansah et al. (2023)
Feedback / adaptation	Immediate feedback and adaptive next steps	Ifenthaler & Yau (2020); Yang et al. (2024)
Pedagogical integration	Inquiry, projects, scaffolding, authentic tasks	Ouyang & Xu (2024); Lawson et al. (2024)

Note. These five mechanisms constitute the thematic synthesis used to develop the E-TEPS framework.

The 32-study evidence base shows a marked increase in publications after 2022, with ten included studies published in 2023 and nine in 2024. AI and GenAI form the largest technology cluster, followed by AR/VR/XR and broader digital, analytics, adaptive, and IoT-oriented approaches. Robotics and digital games form smaller but theoretically distinctive clusters. This distribution suggests that the field is moving toward intelligent and multimodal learning environments rather than relying on a single technology category. Figure 2 summarizes the dominant technology distribution, while Figure 1 presents the publication-year trend.

The distribution also reveals an asymmetry in outcomes. Engagement and general learning outcomes are common across technology types, while problem-solving is more visible in robotics, integrated STEM, games, and immersive learning than in analytics-oriented studies. This does not mean that analytics or AI cannot improve problem-solving; rather, those literatures more often operationalize success through achievement, engagement, personalization, or system performance than through direct measures of problem-solving.

4.2 Mechanism 1: Technology Changes the Learning Activity

Across the evidence base, the strongest educational cases are those in which technology changes the activity students perform. VR enables manipulation and simulation; robotics requires building and debugging; games introduce iterative challenge and feedback; adaptive systems change questions or learning paths; and AI can provide interactive explanation or critique. In these cases, technology becomes a mediator of action rather than a channel for passive content delivery (Ma et al., 2022; Wang et al., 2022; Ouyang & Xu, 2024; Haider et al., 2024a).

This mechanism helps reconcile apparently different findings across studies. A sophisticated platform may have limited effects when used primarily for content consumption, while a relatively simple digital tool can support strong outcomes when embedded in inquiry, project-based, collaborative, or problem-based learning. Therefore, technology integration should be defined by the learning activity it enables, not by the presence of the device or platform alone.

4.3 Mechanism 2: Engagement Sustains Cognitive Activity

The reviewed literature repeatedly links technology use with increased interest, participation, perceived usefulness, or persistence. Digital games and immersive environments provide particularly direct evidence for engagement, while adaptive systems and learning analytics can make progress more visible and support timely feedback (Bond et al., 2020; Wang et al., 2022; Tene et al., 2024). The implication is that engagement can function as a bridge between technology affordance and sustained learning effort.

However, engagement should not be treated as synonymous with screen activity. Students can be highly active on a platform while performing shallow tasks. Cognitive engagement therefore becomes particularly important for STEM, because meaningful learning requires explanation, strategy use, reasoning, reflection, and transfer. Technology designs that include feedback, choice, authentic problems, and opportunities for revision are more likely to produce engagement that supports learning.

4.4 Mechanism 3: Problem-Solving Converts Activity into STEM Competence

Problem-solving emerges as the cognitive mechanism that connects active engagement to STEM competence. When learners use technology to model a system, test a hypothesis, debug a program, manipulate a simulation, or evaluate alternative designs, engagement becomes cognitively productive. Robotics and integrated STEM studies illustrate this pathway particularly clearly, but the same logic can apply to AI-supported inquiry and immersive simulation when tasks require learners to explain and justify decisions (McLure et al., 2022; Darmawansah et al., 2023; Almasri, 2024).

This suggests a distinction between answer-oriented and reasoning-oriented technology use. Answer-oriented use reduces task effort by providing solutions; reasoning-oriented use increases productive cognitive effort by asking students to compare, test, critique, and revise. The second mode is more consistent with STEM education goals. In this sense, the contribution of emerging technology to problem-solving depends on how much technology supports learners in performing the problem-solving process themselves.

4.5 Mechanism 4: Feedback and Adaptation Strengthen Learning Loops

Immediate and actionable feedback is a recurring mechanism across games, adaptive learning, learning analytics, robotics, and AI. Feedback can show whether a simulation worked, indicate why an answer is incorrect, reveal a learner's progress, or suggest the next problem to solve (Ifenthaler & Yau, 2020; Wang et al., 2022; Yang et al., 2024). Adaptive systems can extend this mechanism by using the feedback to change subsequent tasks.

The quality of feedback matters. Feedback should be timely, specific, understandable, and connected to the learner's current goal. Highly automated feedback that is opaque or overwhelming can weaken rather than strengthen learning. This reinforces the importance of pedagogical integration and teacher support as conditions around the technology pathway.

4.6 Mechanism 5: Pedagogical Integration and Context Condition Technology Effects

Technology effectiveness varies because educational technology is embedded in social and instructional systems. Teacher support, intervention duration, instructional strategy, learner characteristics, and technology type all influence outcomes (Ouyang & Xu, 2024). Equity also matters: device access, connectivity, digital confidence, and institutional support influence students' ability to benefit from technology (Haider et al., 2021).

The synthesis therefore treats pedagogical integration as a moderator rather than a background variable. Project-based, inquiry-based, collaborative, and problem-based approaches may amplify the value of emerging technologies because they give technology a clear cognitive purpose. Conversely, technology used without a coherent learning design may generate novelty or convenience without producing equivalent gains in problem-solving or learning outcomes.

Evidence clusters and design signals

- AI / GenAI — The reviewed AI literature emphasizes personalization, feedback, tutoring, explanation, and assessment support, while also highlighting accuracy, cognitive offloading, adoption barriers, and the need for teacher oversight (Haider et al., 2021; Chiu et al., 2023; Cooper, 2023; Almasri, 2024).
- AR / VR / XR — Immersive technologies are most useful when visualization and simulation are embedded in active experimentation, rather than used primarily for novelty or media comparison (Ibáñez-

Espiga & Delgado-Kloos, 2018; Ma et al., 2022; Tene et al., 2024; Yang et al., 2024).

- Robotics — Robotics supports programming, physical action, iterative design, debugging, and STEM competence, with outcomes influenced by instructional strategy, teacher support, and duration (Darmawansah et al., 2023; Ouyang & Xu, 2024; Trapero-González et al., 2024).
- Digital games — Game-based STEM learning benefits from challenge, feedback, repetition, and interaction when these features are aligned with disciplinary learning goals (Wang et al., 2022; Gui et al., 2023).
- Analytics / adaptive learning / IoT — Data become educationally meaningful when they are translated into actionable and interpretable instructional changes rather than simply displayed to learners (Ifenthaler & Yau, 2020; Benita et al., 2021; Haider et al., 2024a, 2024b).
- Engagement and outcomes — Student engagement should be measured across behavioral, emotional, and cognitive dimensions alongside learning outcomes, because activity alone does not guarantee deep learning (Bond et al., 2020; Haider et al., 2021; Le et al., 2023).

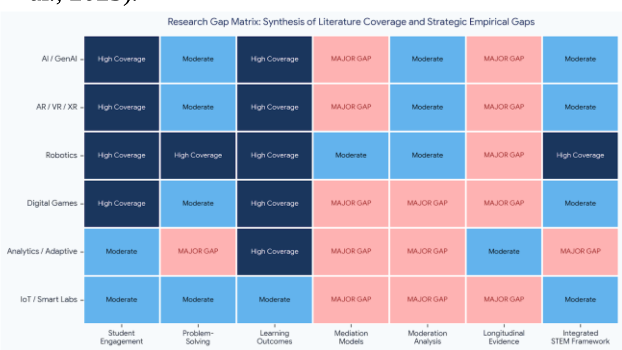

Figure 5. Research gap matrix synthesizing literature coverage across major technology streams and research needs. The matrix highlights stronger coverage for direct engagement and learning outcomes and comparatively larger gaps in mediation, moderation, longitudinal evidence, and integrated STEM frameworks. Ratings are qualitative synthesis labels, not effect sizes.

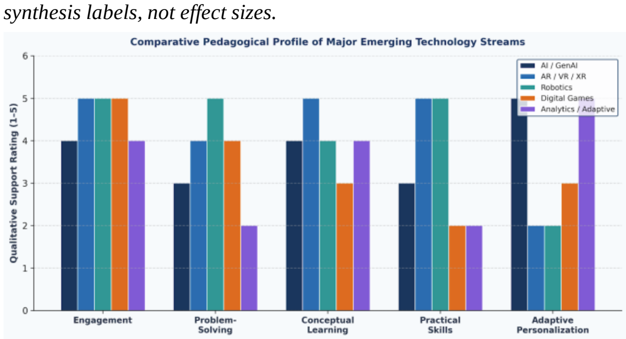

Figure 6. Comparative pedagogical profile of major emerging-technology streams. The chart compares the relative support of AI/GenAI, AR/VR/XR, robotics, digital games, and analytics/adaptive approaches across engagement, problem-solving, conceptual learning, practical skills, and adaptive personalization. Ratings are qualitative author-coded synthesis values, not pooled effect sizes.

5. Emerging Technology–Engagement–Problem-Solving–Learning Outcomes Framework (E-TEPS)

The cross-study synthesis supports a framework in which emerging technologies are not treated as direct and automatic causes of learning. Instead, technology integration changes the learning environment and the activities students perform. These changes influence student engagement; engaged students invest cognitive effort in problem-solving; and successful problem-solving contributes to STEM learning outcomes. Pedagogical integration conditions the strength of this pathway by determining whether the technology is embedded in meaningful tasks, supported by instructors, and aligned with learning objectives. Figures 7 and 8 visualize the proposed mediation and moderation structure.

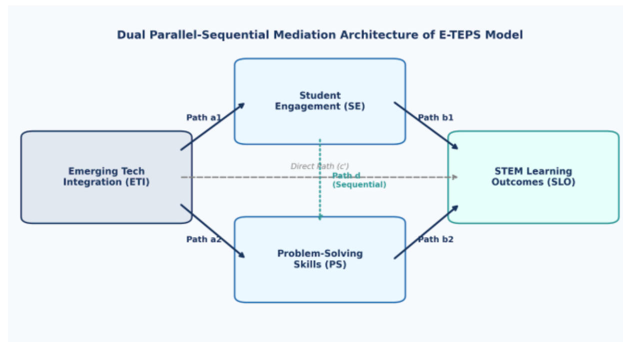

Figure 7. Dual parallel-sequential mediation architecture of the E-TEPS model. The model distinguishes engagement and problem-solving as parallel mediators, while also representing a sequential pathway from engagement to problem-solving and a remaining direct effect from technology integration to STEM learning outcomes.

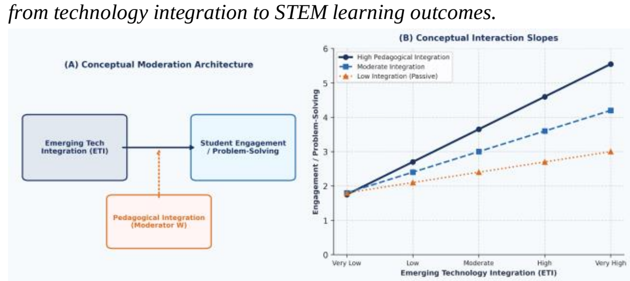

Figure 8. Conceptual moderation architecture and interaction slopes for pedagogical integration. Panel A positions pedagogical integration as a moderator of the technology-to-engagement/problem-solving relationship; Panel B illustrates the expected stronger relationship under higher pedagogical integration. The plotted slopes are conceptual and do not represent empirical parameter estimates.

5.1 Framework Constructs

- Emerging technology integration: purposeful use of AI/GenAI, AR/VR/XR, robotics, games, analytics, adaptive systems, IoT, or combinations of these technologies in STEM learning activities.
- Student engagement: behavioral participation, emotional interest, cognitive investment, persistence, and agentic contribution to learning.
- Problem-solving skills: identifying and representing problems, generating solutions, applying knowledge, testing alternatives, evaluating evidence, and revising solutions.
- STEM learning outcomes: academic achievement, conceptual understanding, practical skill, STEM competence, knowledge retention, and successful transfer or application.

- Pedagogical integration: the degree to which technology is embedded in inquiry, project-based, problem-based, collaborative, or otherwise active learning with appropriate teacher scaffolding.

5.2 Propositions

P1. Greater integration of emerging technologies is positively associated with student engagement when technologies provide meaningful interaction, relevance, feedback, personalization, or authentic representation.

P2. Greater integration of emerging technologies is positively associated with problem-solving skills when learners actively manipulate, test, debug, compare, or revise solutions rather than passively consume information.

P3. Student engagement positively contributes to STEM learning outcomes because sustained behavioral and cognitive investment increases opportunities for practice, reflection, and application.

P4. Problem-solving skills positively contribute to STEM learning outcomes because they support transfer of STEM knowledge to unfamiliar and authentic tasks.

P5. Student engagement mediates the relationship between emerging-technology integration and STEM learning outcomes.

P6. Problem-solving mediates the relationship between emerging-technology integration and STEM learning outcomes.

P7. Pedagogical integration strengthens the positive relationships between emerging-technology integration, student engagement, and problem-solving.

P8. Teacher support, digital readiness, and equitable access condition whether emerging technologies can be used consistently and productively.

5.3 Constructs and Suggested Indicators

Table 4: E-TEPS constructs and suggested indicators

Construct	Core dimensions	Suggested indicators
Technology integration	Interaction; personalization; authenticity; feedback	Purposeful use; active interaction; adaptive support
Student engagement	Behavioral; emotional; cognitive; agentic	Participation; interest; effort; persistence; strategy use
Problem-solving	Identification; generation; testing; evaluation; revision	Analyze; compare; test; evaluate; revise
STEM outcomes	Achievement; understanding; skills; competence; transfer	Performance; mastery; application; retention
Pedagogical integration	Inquiry; project/problem-based; collaboration	Authentic tasks; scaffolding; alignment; teacher mediation
Contextual conditions	Access; readiness; equity; privacy; governance	Connectivity; digital confidence; accessibility; responsible use

- Emerging technology integration: technology variety, interaction, personalization, authenticity, feedback, and purposeful use within STEM activities (Leavy et al., 2023; Wang et al., 2024).
- Student engagement: participation, interest, effort, persistence, cognitive strategy use, and contribution to the learning process (Bond et al., 2020; Haider et al., 2021; Tene et al., 2024).
- Problem-solving: problem identification, solution generation, application, testing, evaluation, and revision (McLure et al., 2022; Darmawansah et al., 2023; Trapero-González et al., 2024).
- STEM learning outcomes: achievement, conceptual understanding, practical skill, STEM competence, retention, and transfer (Wang et al., 2022; Ma et al., 2022; Yang et al., 2024; Ouyang & Xu, 2024).
- Pedagogical integration: inquiry, project-based and problem-based learning, collaboration, feedback, and teacher scaffolding (Le et al., 2023; McLure et al., 2022; Ouyang & Xu, 2024).
- Contextual conditions: access, digital readiness, privacy, equity, institutional support, and responsible technology governance (Haider et al., 2021; Chiu et al., 2023; Haider et al., 2023).

6. Design Principles for Emerging-Technology STEM Education

6.1 Design Around the STEM Problem, Not the Technology

The literature suggests that institutions should begin with the learning problem and desired STEM practice before selecting a technology. If the goal is spatial reasoning, AR/VR may be appropriate; if the goal is iterative engineering design, robotics may be more useful; if the goal is adaptive practice, analytics or AI may be more suitable. The selection process should therefore start with learning objectives, then identify the cognitive activity required, and only then choose the technology that best supports that activity.

6.2 Make Students Do More Than Consume

Technology should increase opportunities to investigate, construct, test, communicate, and revise. Active tasks are especially important for problem-solving. Instructors can require students to document decisions, compare solutions, explain errors, and reflect on the limits of AI or simulation outputs. This preserves the learner's cognitive role while using technology to increase information access and feedback quality.

6.3 Use AI as a Reasoning Partner, Not an Answer Engine

AI can be embedded in STEM activities as a source of questions, counterarguments, alternative explanations, or formative feedback. Students can be asked to verify AI-generated claims, identify weaknesses, compare solutions, or explain why one solution is superior. Such design is more consistent with problem-solving development than direct answer generation (Cooper, 2023; Lo, 2023; Almasri, 2024).

6.4 Preserve Teacher Mediation

Teachers remain necessary for interpreting learner context, identifying misconceptions, choosing appropriate interventions, and maintaining disciplinary rigor. Educational technology should therefore augment rather than replace teacher judgment. This is consistent with evidence that instructor support and instructional strategy moderate technology effects (Ouyang & Xu, 2024).

6.5 Design for Equity, Accessibility, and Trust

Digital inequity can prevent students from benefiting equally from emerging technologies. Institutions should consider device access, connectivity, digital literacy, accessibility, language, privacy, and data governance when implementing technology-supported STEM learning. Equity is therefore a design variable rather than a secondary implementation issue (Haider et al., 2021; Chiu et al., 2023).

7. Discussion

The central finding of this synthesis is that emerging technologies influence STEM learning through an intermediate chain of activity and cognition rather than through technological exposure alone. Technologies create affordances for visualization, adaptation, simulation, feedback, and interaction; students respond through engagement; engagement sustains activity; and problem-solving converts that activity into disciplinary learning. The pathway therefore provides a useful explanation for why broadly positive findings can coexist with substantial differences across individual studies.

The synthesis also clarifies why problem-solving deserves to be positioned between engagement and learning outcomes. Engagement is necessary but not sufficient. A student may be motivated by a game or excited by VR without developing transferable reasoning skills. Problem-solving adds the cognitive bridge: learners must identify a task, apply knowledge, evaluate evidence, make decisions, and revise solutions. The technology is educationally valuable when it supports these operations rather than bypassing them.

The findings further suggest that emerging technologies should be evaluated according to pedagogical fit. Ouyang and Xu (2024) found variation in robotics effects across instructional conditions, while Lawson et al. (2024) showed that VR studies can confound the technology with instructional design. Similar concerns appear in AI research, where usefulness depends on task design, teacher preparation, accuracy, and learner agency (Chiu et al., 2023; Almasri, 2024). This suggests that future research should measure technology integration quality rather than simple exposure or frequency of use.

Another important conclusion concerns convergence. AI, analytics, adaptive learning, immersive technology, and connected devices are increasingly likely to be combined. A smart STEM environment may use sensors to collect data, analytics to interpret it, AI to recommend support, VR to simulate a system, and dashboards to provide feedback. The research challenge therefore shifts from evaluating isolated tools to understanding integrated learning ecosystems. The E-TEPS framework offers a starting point for that transition.

8. Theoretical and Practical Implications

8.1 Theoretical Implications

The paper contributes an integrative perspective that connects technology affordances with learning processes and outcomes. It extends technology-adoption perspectives by treating engagement and problem-solving as learning mechanisms, and it complements constructivist views by emphasizing active interaction with problems and environments. It also responds to the literature's fragmentation by placing different technologies within a common process model rather than assuming that every technology produces learning through the same mechanism.

8.2 Practical Implications

For STEM instructors, the findings imply that technology selection should begin with the learning objective and the desired student activity. For curriculum designers, technology should be embedded in authentic problems, inquiry, design, or projects. For institutions, teacher professional development should cover not only technical use but also task design, AI literacy, assessment, data ethics, and inclusive access. For developers, the priority should be actionable feedback, transparency, learner control, and interoperability rather than technology novelty alone.

8.3. Research agenda emerging from the synthesis
visualizes this agenda as a staged roadmap.

- Single-technology interventions should be complemented by comparative studies that examine mechanisms across technology types and combinations.
- Direct achievement measures should be supplemented with mediation tests that examine engagement and problem-solving as explanatory mechanisms.
- Short interventions should be complemented by longitudinal designs that examine sustained learning and technology effects over time.
- Technology-centered evaluation should be expanded to include pedagogical integration, teacher scaffolding, task design, and learner agency.
- Future research should directly examine access, digital readiness, privacy, language, and algorithmic fairness rather than discussing equity only as a limitation.
- Self-report measures should be combined with performance tasks, learning logs, platform telemetry, and classroom observation.

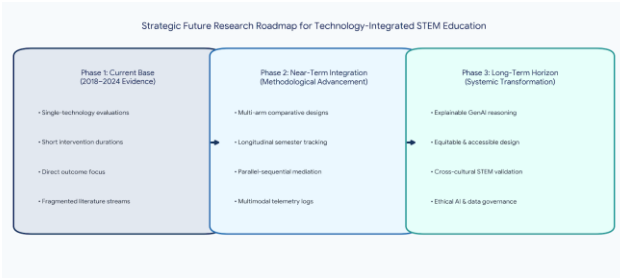

Figure 9. Strategic future research roadmap for technology-integrated STEM education. The roadmap moves from the 2018–2024 evidence base toward comparative and longitudinal designs, multimodal measurement, explainable and equitable AI, cross-cultural validation, and responsible data governance.

Table 5: Priority research agenda derived from the reviewed evidence

Priority	**Current gap**	**Recommended design**
Comparative technology studies	Single-technology evaluations dominate	Compare modalities under equivalent pedagogical tasks
Mediation testing	Engagement and problem-solving often separated	SEM/PLS-SEM with mediation analysis
Longitudinal evidence	Many interventions are short-term	Semester-long or multi-semester tracking
Pedagogical integration	Exposure easier to measure than instructional fit	Measure task design, scaffolding, learner agency
Multimodal measurement	Heavy reliance on self-report	Combine surveys, performance, logs, telemetry, observation
Equity and governance	Often treated as contextual concerns	Include access, privacy, language, fairness, readiness

9. Limitations and Future Research

This study is an integrative literature review rather than a meta-analysis, so it does not estimate a single pooled effect size. The 32-study corpus was purposively assembled around open accessibility, topical relevance, and the 2018–2024 publication window. As a result, relevant studies outside the selected open-access set may be absent. The thematic coding and evidence-emphasis visualizations are interpretive synthesis tools rather than statistical estimates.

The framework should be empirically validated with real student data. A useful next step is to operationalize E-TEPS as a multi-construct survey and performance model and test it using PLS-SEM or covariance-based SEM. Mediation analysis can examine whether engagement and problem-solving explain learning outcomes, while moderation analysis can test whether pedagogical integration strengthens the technology pathway. Longitudinal and mixed-method designs would be particularly valuable because technology effects are dynamic and context-dependent.

Future empirical research should also compare technology modalities under equivalent pedagogical designs. For example, AI, VR, and robotics could be compared when all are embedded in the same problem-based STEM activity. Researchers should combine self-report measures with behavioral and performance evidence, such as learning logs, problem-solving assessments, and classroom observations. Equity and governance should be incorporated directly into study designs rather than treated solely as discussion points.

10. Conclusion

Emerging technologies offer substantial opportunities to enrich STEM education, but the evidence does not support a simple conclusion that technology itself guarantees improved learning. Across 32 studies published from 2018 through 2024, the strongest recurring pattern is a process in which technologies change learning activities, students become more engaged, engagement supports problem-solving, and successful problem-solving contributes to STEM learning outcomes. The strength of this pathway depends on pedagogical integration, teacher support, learner agency, task design, and contextual conditions.

The proposed E-TEPS framework brings these mechanisms together and provides a basis for evaluating emerging technologies according to the learning processes they enable. The framework shifts attention from technology novelty toward purposeful integration, cognitive activity, problem-solving, and measurable learning outcomes. Future research should empirically test these relationships with longitudinal, multimodal, and context-sensitive designs so that STEM education can move from technology adoption toward evidence-based and learner-centered technology integration.

References

Aguilar, D., & Pifarré Turmo, M. (2019). Promoting social creativity in science education with digital technology to overcome inequalities: A scoping review. *Frontiers in Psychology, 10*, 1474. https://doi.org/10.3389/fpsyg.2019.01474

Almasri, F. (2024). Exploring the impact of artificial intelligence in teaching and learning of science: A systematic review of empirical research. *Research in Science Education, 54*, 977–997. https://doi.org/10.1007/s11165-024-10176-3

Benita, F., Virupaksha, D., Wilhelm, E., & Tunçer, B. (2021). A smart learning ecosystem design for delivering data-driven thinking in STEM education. *Smart Learning Environments, 8*, 11. https://doi.org/10.1186/s40561-021-00153-y

Bölek, K. A., De Jong, G., & Henssen, D. (2021). The effectiveness of the use of augmented reality in anatomy education: A systematic review and meta-analysis. *Scientific Reports, 11*, 15292. https://doi.org/10.1038/s41598-021-94721-4

Bond, M., Buntins, K., Bedenlier, S., Zawacki-Richter, O., & Kerres, M. (2020). Mapping research in student engagement and educational technology in higher education: A systematic evidence map. *International Journal of Educational Technology in*

Higher Education, 17, 2. https://doi.org/10.1186/s41239-019-0176-8

Chiu, T. K. F., Xia, Q., Zhou, X., Chai, C. S., & Cheng, M. (2023). Systematic literature review on opportunities, challenges, and future research recommendations of artificial intelligence in education. *Computers and Education: Artificial Intelligence, 4*, 100118. https://doi.org/10.1016/j.caeai.2022.100118

Cooper, G. (2023). Examining science education in ChatGPT: An exploratory study of generative artificial intelligence. *Journal of Science Education and Technology, 32*, 444–452. https://doi.org/10.1007/s10956-023-10039-y

Darmawansah, D., Hwang, G.-J., Chen, M.-R. A., & Liang, J.-C. (2023). Trends and research foci of robotics-based STEM education: A systematic review from diverse angles based on the technology-based learning model. *International Journal of STEM Education, 10*, 12. https://doi.org/10.1186/s40594-023-00400-3

de Sousa, E. B. G., Alexandre, B., Ferreira Mello, R., Pontual Falcão, T., Vesin, B., & Gašević, D. (2021). Applications of learning analytics in high schools: A systematic literature review. *Frontiers in Artificial Intelligence, 4*, 737891. https://doi.org/10.3389/frai.2021.737891

del Cerro Velázquez, F., & Morales Méndez, G. (2021). Systematic review of the development of spatial intelligence through augmented reality in STEM knowledge areas. *Mathematics, 9*(23), 3067. https://doi.org/10.3390/math9233067

Elkhodr, M., Gide, E., Wu, R., & Darwish, O. (2023). ICT students' perceptions towards ChatGPT: An experimental reflective lab analysis. *STEM Education, 3*(2), 70–88. https://doi.org/10.3934/steme.2023006

Gui, Y., Cai, Z., Yang, Y., Kong, L., Fan, X., & Tai, R. H. (2023). Effectiveness of digital educational game and game design in STEM learning: A meta-analytic review. *International Journal of STEM Education, 10*, 36. https://doi.org/10.1186/s40594-023-00424-9

Haider, K., Alam, M. R. U., & Mariz, O. A. (2021). Artificial intelligence in education: A systematic review and bibliometric topic modeling analysis of applications, challenges, and future directions. *US Journal of New Insights in Tech & Education, 1*(1). https://www.edtechinsights.org/article/913c99a5-a5c3-4128-8bc2-6035715e07c0

Haider, K., Alam, M. R. U., & Mariz, O. A. (2024a). Comparative effectiveness of adaptive learning platforms in STEM education: A systematic review. *US Journal of New Insights in Tech & Education, 4*(1). https://www.edtechinsights.org/article/29d2b0fc-8ff0-4c65-af81-dbbf62575270

Haider, K., Alam, M. R. U., & Mariz, O. A. (2024b). Designing smart learning environments: Integrating IoT and sensor data for personalized instruction. *US Journal of New Insights in Tech & Education, 4*(1). https://www.edtechinsights.org/article/1e9c6bf8-26ab-4efa-a7c8-d59a46335ed8

Haider, K., Gupta, M. S., & Alam, M. R. U. (2023). Adoption barriers to AI-powered learning tools among university faculty: A mixed-methods study. *US Journal of New Insights in Tech & Education, 3*(1). https://www.edtechinsights.org/article/09174027-f905-4e04-9645-9eeee122c6c4

Haider, K., Hasan, S., & Alam, M. R. U. (2021). Technology-enhanced learning in the COVID-19 era: A systematic review of online education platforms, student engagement, and digital equity. *US Journal of New Insights in Tech & Education, 1*(1). https://www.edtechinsights.org/article/929fcc41-94c1-49eb-9c13-d8de8b206f0c

Ibáñez-Espiga, M.-B., & Delgado-Kloos, C. (2018). Augmented reality for STEM learning: A systematic review. *Computers & Education, 123*, 109–123. https://doi.org/10.1016/j.compedu.2018.05.002

Ifenthaler, D., & Yau, J. Y.-K. (2020). Utilising learning analytics to support study success in higher education: A systematic review. *Educational Technology Research and Development, 68*, 1961–1990. https://doi.org/10.1007/s11423-020-09788-z

Lawson, A. P., Martella, A. M., LaBonte, K., Delgado, C. Y., Zhao, F., Gluck, J. A., Munns, M. E., & Wells LeRoy, A. (2024). Confounded or controlled? A systematic review of media comparison studies involving immersive virtual reality for STEM education. *Educational Psychology Review, 36*, 69. https://doi.org/10.1007/s10648-024-09908-8

Le, H. C., Nguyen, V. H., & Nguyen, T. L. (2023). Integrated STEM approaches and associated outcomes of K-12 student learning: A systematic review. *Education Sciences, 13*(3), 297. https://doi.org/10.3390/educsci13030297

Leavy, A., Dick, L., Meletiou-Mavrotheris, M., Paparistodemou, E., & Stylianou, E. (2023). The prevalence and use of emerging technologies in STEAM education: A systematic review of the literature. *Journal of Computer Assisted Learning, 39*(4), 1061–1082. https://doi.org/10.1111/jcal.12806

Lo, C. K. (2023). What is the impact of ChatGPT on education? A rapid review of the literature. *Education Sciences, 13*(4), 410. https://doi.org/10.3390/educsci13040410

Ma, Y., Zhang, L., & Wu, M. (2022). Research on the influence of virtual reality on the learning effect of technical skills of science and engineering college students: Meta-analysis based on 32 empirical studies. *International Journal of Digital Multimedia Broadcasting, 2022*, 6202370. https://doi.org/10.1155/2022/6202370

McLure, F. I., Tang, K.-S., & Williams, P. J. (2022). What do integrated STEM projects look like in middle school and high school classrooms? A systematic literature review of empirical studies of iSTEM projects. *International Journal of STEM Education, 9*, 73. https://doi.org/10.1186/s40594-022-00390-8

Montenegro-Rueda, M., Fernández-Cerero, J., Fernández-Batanero, J. M., & López-Meneses, E. (2023). Impact of the implementation of ChatGPT in education: A systematic review. *Computers, 12*(8), 153. https://doi.org/10.3390/computers12080153

Ouyang, F., & Xu, W. (2024). The effects of educational robotics in STEM education: A multilevel meta-analysis. *International Journal of STEM Education, 11*, 7. https://doi.org/10.1186/s40594-024-00469-4

Tene, T., Marcatoma Tixi, J. A., Palacios Robalino, M. L., Mendoza Salazar, M. J., Vacacela Gomez, C., & Bellucci, S. (2024). Integrating immersive technologies with STEM education: A systematic review. *Frontiers in Education, 9*, 1410163. https://doi.org/10.3389/feduc.2024.1410163

Trapero-González, I., Hinojo-Lucena, F. J., Romero-Rodríguez, J.-M., & Martínez-Menéndez, A. (2024). Didactic impact of educational robotics on the development of STEM competence in primary education: A systematic review and meta-analysis. *Frontiers in Education, 9*, 1480908. https://doi.org/10.3389/feduc.2024.1480908

Wang, L.-H., Chen, B., Hwang, G.-J., Guan, J.-Q., & Wang, Y.-Q. (2022). Effects of digital game-based STEM education on students' learning achievement: A meta-analysis. *International Journal of STEM Education, 9*, 26. https://doi.org/10.1186/s40594-022-00344-0

Wang, S., Wang, F., Zhu, Z., Wang, J., Tran, T., & Du, Z. (2024). Artificial intelligence in education: A systematic literature review. *Expert Systems with Applications, 252*, 124167. https://doi.org/10.1016/j.eswa.2024.124167

Yang, C., Zhang, J., Hu, Y., Yang, X., Chen, M., Shan, M., & Li, L. (2024). The impact of virtual reality on practical skills for students in science and engineering education: A meta-analysis. *International Journal of STEM Education, 11*, 28. https://doi.org/10.1186/s40594-024-00487-2