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STEM-Based Science Instruction with Artificial Intelligence Integration: An Educational Vision for the 21st Century

Yapay Zekâ Entegrasyonu ile STEM Tabanlı Fen Bilimleri Eğitimi: 21. Yüzyıl İçin Bir Eğitim Vizyonu

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ABSTRACT: This study presents a comprehensive literature review investigating the transformative role of Artificial Intelligence in STEM-based science instruction to shape an educational vision for the 21st century. The methodology employs a systematic search across major academic databases, including SSCI, ESCI, ERIC, Scopus, Web of Science, TR-Index, and Google Scholar, covering the period from 2016 to 2025. Following a rigorous screening process based on predefined inclusion and exclusion criteria—focusing on peer-reviewed articles, project-based learning, and 21st-century skills—a total of 56 studies were selected. The findings highlight a pedagogical paradigm shift where AI tools facilitate personalized feedback, predictive analytics, and enhanced teacher practices within STEM frameworks. Based on these insights, the study articulates an explicit educational vision characterized by the optimization of interdisciplinary STEM applications and the evolution of teacher roles from lecturers to facilitators in AI-integrated environments. This refined framework aims to provide a transparent and actionable roadmap for educators and curriculum designers in the modern era.

Keywords: Artificial intelligence in education, STEM education, science curriculum, project-based learning, 21st century skills.

ÖZ: Bu çalışma, 21. yüzyıl için bir eğitim vizyonu oluşturmak amacıyla STEM temelli fen öğretiminde Yapay Zekânın (YZ) dönüştürücü rolünü inceleyen kapsamlı bir literatür taraması sunmaktadır. Metodoloji, 2016 ile 2025 arasındaki dönemi kapsayan SSCI, ESCI, ERIC, Scopus, Web of Science, Tr Dizin ve Google Scholar gibi başlıca akademik veri tabanlarında sistematik bir arama yapılmasını içermektedir. Önceden tanımlanmış dahil etme ve hariç tutma kriterlerine dayalı titiz bir tarama sürecinin ardından —makaleler, proje tabanlı öğrenme ve 21. yüzyıl becerilerine odaklanılarak—toplam 56 çalışma seçilmiştir. Bulgular, AI araçlarının STEM çerçeveleri içinde kişiselleştirilmiş geri bildirim, tahmine dayalı analitik ve gelişmiş öğretmen uygulamalarını kolaylaştırdığı bir pedagojik paradigma değişimini vurgulamaktadır. Bu içgörülere dayanarak, çalışma, disiplinler arası STEM uygulamalarının optimizasyonu ve AI entegre ortamlarda öğretmen rollerinin ders verenlerden kolaylaştırıcılara doğru evrimleşmesi ile karakterize edilen açık bir eğitim vizyonunu ortaya koymaktadır. Bu araştırma çerçevesi bağlamında, modern çağda eğitimciler ve müfredat tasarımcıları için şeffaf ve uygulanabilir bir yol haritası sağlamayı amaçlamaktadır.

Anahtar kelimeler: Eğitimde yapay zekâ, STEM eğitimi, fen müfredatı, proje tabanlı öğrenme, 21. yüzyıl becerileri.

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The integration of Artificial Intelligence (AI) into science education represents a paradigm shift in the development of 21st-century learning environments. This transformation has been particularly pronounced in the field of STEM (Science, Technology, Engineering, and Mathematics), where AI technologies are reshaping both instructional methods and student learning outcomes (Huang et al., 2023). This paradigm shift refers to the transition from traditional teacher-centered instruction toward learner-centered, AI-supported, adaptive, and data-driven learning environments. In this new paradigm, students actively construct knowledge through interactive and personalized learning experiences supported by intelligent technologies. As educational systems evolve, the imperative to foster computational thinking, personalized learning pathways, and data-informed decision-making becomes increasingly critical (Yadav et al., 2016). Within this context, science education is no longer confined to traditional textbook-driven instruction but is instead transitioning into an interactive, problem-based and technology-enhanced experience. This change is driven by the necessity to equip students with cognitive flexibility, creative problem-solving, and digital fluency—21st century skills required to navigate an AI-augmented World (Bozkurt, 2023).

The growing presence of AI-powered tools in science classrooms is also transforming how students interact with content and how teachers design and deliver instruction. Intelligent tutoring systems, adaptive feedback platforms, and AI-supported laboratory simulations provide learners with dynamic opportunities for inquiry-based learning (McDaniel, 2025). Furthermore, these tools are instrumental in expanding access to complex scientific concepts through visualization, automation, and predictive analytics (Kavitha & Joshith, 2024). As AI continues to permeate every aspect of education, a deeper understanding of its implications in STEM fields—particularly in science teaching—has become a central concern for educators, policymakers, and researchers alike (Holmes et al., 2019).

The integration of AI within STEM-based science instruction fundamentally redefines the student's role from a passive recipient of information to an active agent of inquiry. Through AI-enhanced Project-Based Learning, students engage in solving multifaceted, real-world problems that require the simultaneous application of scientific reasoning and technological tools. AI systems provide personalized, feedback-rich environments that diagnose individual misconceptions and offer tailored interventions, thereby supporting students' cognitive and metacognitive development. Furthermore, these technologies enable adaptive learning pathways, allowing learners to progress at their own pace while developing essential 21st-century skills, including critical thinking, digital literacy, and collaboration. However, the success of this vision is contingent upon student readiness**,** emphasizing the need for learners to cultivate a mindset oriented toward innovation and ethical reasoning in AI-supported environments.

Purpose of the Study

This study aims to provide a comprehensive literature-based exploration of how Artificial Intelligence is being integrated into STEM-based science instruction to shape an educational vision fit for the demands of the 21st century. In the context of modern education, 21st-century skills encompass a broad spectrum of competencies essential for

navigating an increasingly digitalized world. Central to this framework are the 4Cs—Critical Thinking, Communication, Collaboration, and Creativity—alongside Information, Media, and Technology literacy (Çelik et al., 2024; Ng et al., 2023). These skills are not merely supplementary but are foundational to student success in a globalized workforce (Strong et al., 2020). Within STEM education, these competencies are cultivated through active inquiry and the application of scientific reasoning to real-world challenges (Zhan et al., 2023). The integration of Artificial Intelligence further optimizes this process by providing adaptive learning environments that offer personalized feedback and diagnostic interventions tailored to individual student needs (Çelik et al., 2024). Consequently, the educational vision proposed in this study is developed through a systematic synthesis of these AI-driven affordances, aiming to transition the pedagogical focus from traditional content delivery to a competence-based, interdisciplinary STEM framework (Heilala et al., 2023).

Rather than presenting empirical data or thematic analyses, this paper critically reviews existing literature to understand the evolution, implementation, and impact of AI tools in science education. It investigates how AI has contributed to project-based learning, supported teacher practices, and promoted the development of higher-order thinking skills within STEM frameworks (Ouyang et al., 2022).

Moreover, the study seeks to map the current state of research concerning AI applications in science instruction, comparing national and international perspectives, and identifying both opportunities and limitations. It provides an in-depth synthesis of scholarly works that highlight innovations in AI-assisted curriculum design, instructional delivery, and assessment mechanisms in K–12 and secondary science education settings (Wang et al., 2024; Casal Otero et al., 2023). The findings are expected to inform educators, curriculum designers, and education technology developers aiming to enhance pedagogical effectiveness through AI-supported methodologies (Rehman et al., 2024; Valenzuela, 2025).

The primary purpose of this study is to systematically synthesize current literature (2016–2025) to evaluate the impact of Artificial Intelligence integration on STEM-based science instruction and to propose a future-ready educational vision. To provide a granular analysis of this integration, the literature review was guided by the following research questions (RQ):

RQ1: How do AI-based tools facilitate Project-Based Learning and inquiry-driven activities in STEM education?

RQ2: In what ways does AI integration contribute to the development of Higher-Order Thinking Skills and 21st-century competencies (the 4Cs: Critical Thinking, Communication, Collaboration, and Creativity)?

RQ3: What are the affordances of AI-driven adaptive learning systems for providing personalized feedback and diagnostic interventions in science classrooms?

RQ4: How does the synergy between AI and STEM education redefine the pedagogical roles of teachers and students within a 21st-century educational vision?

Scope and Limitations

This review article is limited to literature published between 2016 and 2025, focusing specifically on peer-reviewed journal articles, systematic reviews, and high-

quality reports that address the intersection of AI and science education within a STEM framework. The inclusion criteria prioritized sources that explore classroom applications, project-based learning implementations, and skill development associated with AI-enhanced instruction (Kunnath & Botes, 2025; Heeg & Avraamidou, 2023). Studies focusing solely on AI technical development, without educational implications, were excluded.

The review does not involve original empirical data collection or meta-analytic computations. This study utilizes a systematic literature synthesis rather than original empirical data collection or meta-analytic computations. The rationale for this approach is two-fold. First, the primary aim is to conceptualize a broad educational vision that integrates multifaceted variables such as teacher roles, student agency, and AI-driven adaptive learning—a goal that requires a deep qualitative analysis of diverse pedagogical frameworks. Second, the current research landscape of AI in STEM is characterized by significant methodological heterogeneity. With research volume expanding by nearly 95% in the last decade, studies vary widely in their application of AI (from intelligent tutoring to predictive modeling) and their focus on different 21st-century competencies. Consequently, a meta-analysis would be premature and potentially reductive, whereas a systematic synthesis allows for the extraction of overarching pedagogical affordances and the identification of gaps in the interdisciplinary synergy between AI and STEM. This approach provides the necessary theoretical depth to transition from individual study findings to a scalable, future-ready educational roadmap. As such, it is constrained to the descriptive and comparative synthesis of existing academic knowledge. While efforts were made to include a diverse range of geographical and cultural contexts, the review is inherently limited by the availability and accessibility of English-language academic literature (Jaramillo & Chiappe, 2024; Kotsis, 2024). Additionally, though the review touches upon implications for teacher training and curriculum development, it does not provide a framework for implementation or policymaking, which may be considered in future empirical studies (Zhai, 2024).

Key Concepts and Definitions

To establish a consistent terminological foundation, it is essential to define several key concepts central to this study. Artificial Intelligence (AI) in education refers to computer systems capable of performing tasks that typically require human intelligence, such as personalized feedback, natural language processing, and predictive analytics in learning environments (Holmes et al., 2019; Bozkurt, 2023). Within science education, AI encompasses intelligent tutoring systems, virtual laboratories, and AI-enhanced assessment tools that adapt instruction to student needs (Huang et al., 2023).

STEM Education represents an interdisciplinary approach to teaching that integrates science, technology, engineering, and mathematics with the aim of fostering inquiry-based problem-solving and real-world relevance (Mishra & Mehta, 2017). Project-Based Learning (PBL) is defined as a student-centered pedagogical approach that involves the exploration of complex questions or problems over an extended period, culminating in the creation of a final product or presentation (Ruiz Viruel et al., 2025; Rehman et al., 2024).

21st Century Skills include critical thinking, collaboration, creativity, communication, digital literacy, and adaptability—capabilities that are essential for success in an increasingly complex and technological world (Yadav et al., 2016; McDaniel, 2025). These skills are often emphasized within STEM education, particularly when enhanced through AI-enabled tools and platforms. Lastly, AI-Supported Instruction in science involves the strategic use of AI technologies to facilitate conceptual understanding, personalize content delivery, and promote student engagement through interactive and adaptive learning environments (Kavitha & Joshith, 2024).

In summary, this introductory section has framed the significance, objectives, limitations, and conceptual scope of the current literature review. The integration of AI into STEM-based science education is an emergent and dynamic field that holds transformative potential for teaching and learning in the 21st century. The subsequent sections of the paper will delve deeper into the literature to unpack how AI tools are shaping science education and advancing pedagogical innovation.

Method

This study is designed as a Systematic Literature Review, a research methodology fundamental for evidence synthesis that prioritizes systematicity, transparency, and replicability (Amjad et al., 2023). To ensure a standardized approach and enhance the quality of reporting, the review strictly adheres to the PRISMA 2020 declaration, utilizing its 27-item checklist and rigorous procedural framework to maintain methodological integrity (Sánchez Serrano, Pedraza Navarro & Donoso González, 2022). The systematic process was executed through four distinct phases: first, a comprehensive identification search was performed across global academic databases, such as Scopus and Web of Science, to gather all potentially relevant records. Subsequently, these records underwent a rigorous screening process where titles and abstracts were evaluated against predefined inclusion and exclusion criteria to isolate literature specifically relevant to AI in STEM education (Pejić Bach & Cerpa, 2018). This was followed by a full-text eligibility analysis to assess pedagogical depth and ensure that only high-quality, peer-reviewed data sources were included, thereby mitigating potential selection bias.

Finally, the selected sample was subjected to inclusion for thematic synthesis, utilizing standardized data extraction forms to systematically capture key findings and AI affordances (Amjad et al., 2023). By employing this structured methodology, the study transcends subjective interpretation to provide an objective, evidence-based vision for the future of science instruction in the era of artificial intelligence.

Inclusion and Exclusion Criteria

The literature selection for this review was guided by a set of well-defined inclusion and exclusion criteria to ensure the relevance, credibility, and academic rigor of the sources. Included studies were those published between 2016 and 2025 that specifically addressed the intersection of artificial intelligence (AI) and STEM-based science education. Peer-reviewed journal articles, systematic literature reviews, and conceptual papers discussing classroom applications of AI in science instruction were prioritized. Publications emphasizing project-based learning, 21st-century skills, or AI-

supported instructional strategies within science curricula were also deemed relevant (Bozkurt, 2023). The systematic search across databases initially yielded a total of 112 records. Following the removal of duplicates and a title/abstract screening, 82 articles were assessed for full-text eligibility. Ultimately, 56 peer-reviewed articles published in 68 different international and domestic journals were selected for inclusion in this review.

Exclusion criteria involved studies with a purely technical or engineering focus lacking pedagogical implications, opinion pieces without empirical or theoretical grounding, and sources not available in English. Reports that focused exclusively on higher education settings were generally excluded, unless they provided transferable frameworks applicable to K–12 contexts (Holmes et al., 2019; Casal Otero et al., 2023). This deliberate filtering aimed to build a focused and education-oriented literature base. Furthermore, only open-access or institutionally available resources were used, ensuring replicability and transparency in source accessibility (Kunnath & Botes, 2025; Kavitha & Joshith, 2024).

To maintain high academic standards, the selection of literature was governed by specific indexing and quality criteria. Priority was given to peer-reviewed articles indexed in global databases such as SSCI, ESCI, ERIC, Scopus, Web of Science, TR-Index and Google Scholar ensuring that the findings are grounded in rigorous scholarly research. The review specifically preferred journals with a strong focus on educational technology and interdisciplinary STEM research, as these publications offer the most relevant insights into the integration of Artificial Intelligence in science instruction. Both international journals and prominent national publications were included to provide a balanced perspective on global trends and local implementation strategies. Sources that were not peer-reviewed, such as conference abstracts without full papers or non-academic blog posts, were excluded to preserve the theoretical and empirical integrity of the proposed educational vision.

Databases and Keywords Used

The literature was gathered using searches conducted across multiple academic databases, including SSCI, ESCI, ERIC, Scopus, Web of Science, TR-Index and Google Scholar. These platforms were chosen for their comprehensive coverage of education, technology, and interdisciplinary STEM research. To narrow the results, Boolean search strategies were applied using combinations of keywords such as "artificial intelligence AND science education," "AI AND STEM learning," "AI-supported project-based learning," "21st century skills AND AI," and "AI tutors in K–12 science" (Huang et al., 2023; Wang et al., 2024).

Searches were conducted iteratively, with filters applied to restrict the publication dates to the specified range and to eliminate duplicate results. Keyword combinations were refined over time to identify both broad and niche studies that addressed the integration of AI into science curricula. Priority was given to studies that had a clear educational intervention or model applicable to classroom practice (McDaniel, 2025; Heeg & Avraamidou, 2023). Additionally, references found within selected studies were examined in a backward snowballing approach to discover

foundational literature or overlooked contemporary sources (Rehman et al., 2024; Valenzuela, 2025).

The temporal boundary for this literature review was set from 2016 to 2025 to capture the most transformative era of digital education. The year 2016 is identified as a critical baseline for several reasons. First, it aligns with the widespread formalization of Industry 4.0 principles, which necessitated a transition toward STEM-based science instruction that integrates advanced technologies like AI (Heilala et al., 2023). Second, academic interest in the synergy between AI and 21st-century skills saw a significant upward trend during this period, with a substantial increase in published research focusing on AI-driven adaptive learning and personalized feedback systems (Strong et al., 2020; Ng et al., 2023). Furthermore, key developments in AI—such as the emergence of more accessible large-scale neural networks and intelligent tutoring systems—began to deeply influence classroom practices and curriculum design after 2015 (Çelik et al., 2024). Therefore, starting the review in 2016 allows for a comprehensive analysis of the evolution from early AI experiments to the current, sophisticated integration of AI in STEM environments, providing a robust foundation for the proposed educational vision.

Classification of the Literature

This study employs a hybrid analytical approach, integrating thematic, conceptual, and chronological classification methods. This multi-dimensional strategy is necessary because AI in STEM education requires a convergence of rapidly evolving technical tools and shifting pedagogical frameworks (Abuhassna et al., 2024). While the thematic analysis identifies recurring educational affordances (e.g., adaptive feedback, 4C skills), the chronological component tracks the transition from early intelligent tutoring to modern generative AI systems. This approach ensures that the proposed educational vision is grounded in both the historical trajectory of the field and the immediate needs of contemporary science instruction (Kesgin, 2025).

Initially, articles were grouped based on recurring themes such as AI in project-based learning, teacher perceptions of AI tools, AI for inquiry-based instruction, and skill development related to 21st-century competencies (Mishra & Mehta, 2017). This thematic grouping allowed for deeper analysis of how AI applications address pedagogical objectives in science classrooms.

Subsequently, a conceptual classification was applied to distinguish between foundational theories and applied practices. For example, theoretical discussions on AI's role in transforming learning paradigms (Bozkurt, 2023; Jaramillo & Chiappe, 2024) were separated from empirical studies illustrating classroom implementations and outcomes (Kotsis, 2024). This separation helped contextualize conceptual innovation within practical scenarios. A limited chronological organization was also employed to trace the evolution of AI use in science education, highlighting shifts in focus from AI literacy to adaptive systems and assessment tools over time (Zhai, 2024; Yadav et al., 2016).

This structured classification process ensures a coherent presentation in the following sections of the paper, enabling readers to track developments in the field, assess emerging pedagogical trends, and identify research gaps for future inquiry. By

synthesizing literature through this lens, the study offers both a descriptive and interpretive account of AI's integration into STEM-based science instruction.

Validity and Reliability

The validity and reliability of this systematic review were ensured through several procedural safeguards. To maximize procedural validity, the study followed the PRISMA 2020 protocol, ensuring transparency in the search and selection process (Sohrabi et al., 2021). Reliability was addressed by multiple coders during the screening and data extraction phases (Belur et al., 2018). Two researchers independently assessed the eligibility of the identified articles based on strictly defined inclusion and exclusion criteria to minimize selection bias. In cases where disagreements occurred, a third-party consultation or collaborative discussion was held until a 90% consensus was reached, thereby ensuring high inter-rater consistency.

Conceptual and Theoretical Framework

This section establishes the theoretical and conceptual foundations for the integration of artificial intelligence within STEM learning environments. It provides a comprehensive analysis of three core dimensions: the synergy between AI tools and 21st-century skills—specifically critical thinking, creativity, collaboration, and communication (the 4Cs)—the evolution of pedagogical affordances in science instruction, and the emerging paradigms of human-AI collaboration. Furthermore, the elements of 'AI Tools', 'Global Trends in AI-Integrated STEM Education', and 'Opportunities and Challenges in Implementation' are also addressed separately.

Foundations of STEM in Science Education

STEM education, as an interdisciplinary approach, aims to foster students' scientific literacy, critical thinking, and problem-solving abilities by integrating science, technology, engineering, and mathematics into cohesive learning experiences. The core rationale behind STEM integration in science education lies in preparing students for the increasingly complex and technology-oriented world they inhabit. Rather than treating science as an isolated discipline, STEM-oriented teaching positions it within a broader problem-solving context, often encouraging hands-on inquiry and real-world application. This foundational premise aligns with global educational goals aimed at cultivating innovation, workforce readiness, and civic engagement through science learning (Bozkurt, 2023).

A critical aspect of STEM integration is its emphasis on inquiry-driven learning, where students are encouraged to formulate questions, conduct investigations, and interpret data using cross-disciplinary knowledge (Huang et al., 2023). Such approaches not only promote deeper conceptual understanding but also mirror the authentic practices of scientists and engineers, thereby making science education more engaging and relevant. The design and implementation of STEM-based science instruction often necessitate curricular restructuring, professional development for teachers, and supportive learning environments rich in technology and collaboration (McDaniel, 2025). Thus, the foundations of STEM in science education reflect a holistic pedagogical shift that values both content mastery and transferable skills development.

Project-Based Learning in STEM Curricula

Project-Based Learning (PBL) has emerged as a prominent pedagogical strategy within STEM education due to its capacity to simulate authentic learning contexts and promote student agency. By centering learning around complex, open-ended problems, PBL encourages students to engage in sustained inquiry, collaborate with peers, and construct knowledge through iterative design and reflection (Rehman et al., 2024). In science education, PBL aligns well with the investigative nature of scientific practice, offering students opportunities to experiment, hypothesize, and test ideas while applying interdisciplinary knowledge.

Recent studies underscore the effectiveness of AI-enhanced PBL in fostering deep learning and enhancing student engagement (Ruiz Viruel et al., 2025). For instance, AI tutors can facilitate personalized scaffolding, offer real-time feedback, and adapt instructional content based on learners' performance, thereby enriching the PBL experience (Valenzuela, 2025). Moreover, PBL encourages the development of essential 21st-century skills, including collaboration, communication, and digital literacy—competencies that are crucial for success in both academic and professional domains (Rehman et al., 2024).

Within the STEM context, PBL facilitates the integration of multiple disciplines by allowing students to solve multifaceted problems that require a combination of scientific reasoning, technological tools, mathematical modeling, and engineering design (Wang et al., 2024). Teachers, therefore, act as facilitators and co-learners, guiding students through a dynamic learning process that mirrors real-world challenges. The integration of AI technologies into PBL environments further amplifies these possibilities, enabling adaptive learning pathways and data-driven instructional decisions (Bozkurt, 2023; Kunnath & Botes, 2025).

21st Century Skills in Science Education

The infusion of 21st-century skills into science education has become a cornerstone of contemporary curriculum reform efforts, reflecting the changing demands of society, economy, and technology. These skills, which include critical thinking, creativity, communication, collaboration, and digital literacy, are not only essential for academic achievement but also vital for lifelong learning and global citizenship (Mishra & Mehta, 2017). In the context of science instruction, fostering these competencies requires pedagogical strategies that go beyond rote memorization, emphasizing instead problem-based tasks, exploratory learning, and collaborative activities (Yadav et al., 2016).

STEM education provides an ideal platform for embedding 21st-century skills into instructional practices, particularly when coupled with project-based methodologies and technology-enhanced learning environments. AI integration, in this regard, serves as a powerful enabler of personalized, feedback-rich, and student-centered learning experiences (Jaramillo & Chiappe, 2024). For example, intelligent systems can monitor student progress, diagnose misconceptions, and deliver tailored interventions that support cognitive and metacognitive development (Casal Otero et al., 2023).

In the context of modern science education, these skills are defined within the Partnership for 21st Century Learning (P21) Framework, which is the most prevalent classification used to align student outcomes with STEM-based instruction (Haryani et

al., 2021). This framework categorizes competencies into the 4Cs alongside Information, Media, and Technology Literacy (Mıhladız Turhan & Demirci, 2021). Within scientific inquiry, these skills are not merely supplementary but are foundational to Scientific Literacy, as they enable students to process complex data and engage in evidence-based problem-solving (Öztürk, 2023). By grounding these competencies in the P21 framework, the study emphasizes their role as vital prerequisites for academic achievement, lifelong learning, and professional success in a globalized, AI-driven workforce (Mıhladız Turhan & Demirci, 2021).

Moreover, the development of these skills in science education is not merely about acquiring technical proficiency but also involves cultivating ethical reasoning, adaptability, and a mindset oriented toward innovation and sustainability (Holmes et al., 2019). AI-supported instruction can play a critical role in modeling and reinforcing these competencies by creating dynamic learning scenarios that simulate real-life problems and require multifaceted thinking (Heeg & Avraamidou, 2023). Thus, the integration of 21st-century skills in science education, supported by AI tools, represents a strategic response to the evolving educational landscape.

Artificial Intelligence in Educational Contexts

Artificial Intelligence in education is increasingly viewed not just as a technological advancement but as a transformative force capable of reshaping pedagogical paradigms. In science education specifically, AI enables new forms of learning that are adaptive, interactive, and data informed. AI applications range from intelligent tutoring systems and virtual laboratories to learning analytics platforms and natural language processing tools that support both teachers and students (Huang et al., 2023; Holmes et al., 2019).

One of the core benefits of AI in educational contexts is its capacity to personalize instruction based on learner profiles, preferences, and performance patterns. This personalization allows for differentiated learning experiences that address individual strengths and gaps, thereby improving student outcomes (Bozkurt, 2023; Kavitha & Joshith, 2024). Furthermore, AI technologies can assist teachers by automating routine tasks, facilitating formative assessments, and providing insights into student engagement and progress (Wang et al., 2024). Such affordances contribute to more efficient and effective teaching, freeing up time for meaningful interaction and scaffolding.

However, the integration of AI in educational settings also raises ethical, practical, and pedagogical challenges. Concerns around data privacy, algorithmic bias, and equitable access to technology must be carefully addressed to ensure that AI serves as a tool for inclusion rather than exclusion (Casal Otero et al., 2023; Jaramillo & Chiappe, 2024). Additionally, teachers require targeted professional development to effectively incorporate AI tools into their instructional practices and to critically assess their impact on learning (McDaniel, 2025; Kotsis, 2024). As such, a balanced and reflective approach to AI implementation is essential to realize its full potential in science education.

AI Tools and Techniques for Science Learning

The application of AI tools in science learning encompasses a diverse range of technologies designed to enhance inquiry, experimentation, and conceptual understanding. These tools include virtual laboratories, simulation engines, intelligent tutoring systems, predictive analytics platforms, and adaptive learning environments that respond to student inputs in real time (Kunnath & Botes, 2025; Zhai, 2024). In K–12 contexts, AI-powered tools are particularly valuable for visualizing abstract scientific phenomena, enabling students to manipulate variables and observe outcomes in safe, controlled, and cost-effective environments (Bozkurt, 2023).

Among the most impactful AI techniques used in science instruction are machine learning algorithms that predict student performance and offer targeted interventions, natural language processing tools that support reading comprehension and scientific writing, and neural networks that enable personalized content sequencing (Kavitha & Joshith, 2024). These technologies not only foster individualized learning trajectories but also promote deeper engagement with scientific content by aligning instruction with learners' cognitive needs and interests (Ouyang et al., 2022).

In addition, AI tools facilitate collaborative learning by supporting real-time data sharing, group simulations, and intelligent feedback systems that guide student discourse and decision-making (Valenzuela, 2025; Ruiz Viruel et al., 2025). For teachers, AI provides dashboards and analytics that reveal learning trends, highlight areas of difficulty, and inform instructional planning (Heeg & Avraamidou, 2023). The design of these tools is increasingly influenced by user-centered principles, ensuring that they are intuitive, accessible, and pedagogically grounded (Wang et al., 2024).

Nonetheless, the effective use of AI tools in science education depends heavily on contextual factors such as infrastructure, teacher expertise, curriculum alignment, and student readiness. Addressing these variables requires strategic planning, resource allocation, and stakeholder collaboration (Bozkurt, 2023; Kotsis, 2024). When implemented thoughtfully, AI tools can serve as powerful catalysts for transforming science classrooms into dynamic ecosystems of inquiry, innovation, and personalized learning.

Comparative Review of the Literature

Global Trends in AI-Integrated STEM Education

In recent years, global interest in the integration of artificial intelligence (AI) into STEM education has intensified, reflecting broader trends in digital transformation, educational equity, and workforce readiness. Countries such as the United States, China, South Korea, Finland, and Singapore have been at the forefront of adopting AI-enhanced pedagogical models, emphasizing the need for adaptive, personalized, and inquiry-driven learning environments (Huang et al., 2023; Wang, 2024). These nations have developed national AI-in-education frameworks, invested in digital infrastructure, and provided extensive teacher training to embed AI tools into science education effectively (Holmes et al., 2019; McDaniel, 2025).

For example, in the United States, AI has been applied through intelligent tutoring systems, adaptive assessments, and simulation-based STEM labs designed to foster deeper scientific reasoning and critical thinking. China, on the other hand, has

implemented large-scale AI platforms in schools to support real-time learning analytics and data-driven instructional adjustments (Zhai, 2024). South Korea has introduced AI-focused science curricula in middle schools, while Finland has pioneered national AI literacy campaigns linked with interdisciplinary STEM tasks (Casal Otero et al., 2023). These approaches demonstrate a strong alignment between national education policy and AI integration.

The table below summarizes notable global initiatives that reflect the diversity of AI implementation strategies in STEM-based science education:

Table 1

Global AI-STEM Integration Strategies

Country	**Key Initiatives**
USA	Adaptive learning platforms, AI tutors in science labs
China	AI analytics dashboards, national EdTech networks for STEM
Finland	National AI literacy program integrated with STEM inquiry tasks
South Korea	AI-based science modules and digital assessment systems
Singapore	AI-enhanced collaborative robotics in K–12 STEM settings

The geographical distribution of the included studies reveals a significant concentration in specific regions, primarily the United States, China and Singapore, which is consistent with global trends in AI education research (Zawacki Richter et al., 2019). This concentration is largely attributed to the robust research infrastructure, significant investment in AI development, and the prioritization of STEM-based digital transformation in these nations.

The apparent lack of data from other regions, particularly the Global South (including Africa, Latin America, and parts of Central Asia), highlights a substantial 'geographic diversity gap' in the literature (Khoza & Walt, 2025; Shams et al., 2023). This disparity is driven by several systemic barriers:

1. Infrastructure and Digital Divide: Limited access to high-speed internet and advanced AI tools in underdeveloped regions restricts the implementation and empirical study of these technologies (Khoza & Walt, 2025).
2. Language Barrier: A significant portion of research in regions like South and Central America is published in native languages, which often leads to underrepresentation in English-language academic databases (Bond et al., 2024).
3. Resource Constraints: The high cost of AI integration and a lack of faculty preparedness in many developing nations hinder the large-scale pedagogical experiments required for peer-reviewed publication (Khoza & Walt, 2025)

Although these countries differ in sociocultural and educational contexts, their common emphasis lies in designing scalable AI ecosystems that promote equity, innovation, and learner-centered instruction. Nevertheless, there remains a critical need to evaluate the longitudinal impacts of such interventions and ensure that pedagogical transformation does not become solely technology-driven but remains grounded in sound educational principles (Bozkurt, 2023).

National Contexts: Türkiye and Other Case Studies

In Türkiye, the integration of AI into STEM education is gaining attention but remains in early developmental stages compared to global pioneers. Recent efforts include teacher workshops on AI pedagogy, pilot studies in selected secondary schools, and research initiatives exploring AI-supported project-based learning environments. However, institutional and infrastructural limitations—such as unequal access to digital resources and limited teacher proficiency in AI technologies—hinder widespread adoption (Bozkurt, 2023).

Dağıstan & Taşdemir (2026) found that while teachers in Türkiye recognize the pedagogical value of AI tools in science classrooms, they often feel underprepared to implement them due to lack of professional development and curriculum support. Furthermore, AI initiatives in Türkiye often focus on software development and coding rather than embedding AI meaningfully into science education content. Compared to countries like Finland or South Korea, Türkiye's policy-level engagement with AI in K–12 education remains limited.

A comparative view can be illustrated below:

Table 2

Türkiye vs. Selected Countries in AI-STEM Integration

Aspect	Türkiye	Finland	South Korea
Policy Framework	Emerging, fragmented	National AI strategy for schools	Ministry-led science AI modules
Teacher Training	Sporadic workshops	Government-funded certification	Systematic in-service training
Infrastructure	Uneven access	High digital equity	High-speed EdTech integration
AI Pedagogical Focus	Tech-oriented (coding, robotics)	Concept-oriented STEM inquiry	Skill-based science learning

Other nations such as India and Brazil offer hybrid models of AI in STEM education, where both non-governmental and governmental sectors collaborate to promote low-cost, scalable AI tools. These contexts reveal that innovation is not exclusive to high-income countries, and context-sensitive models can succeed if supported by sustained teacher engagement and policy continuity (Kotsis, 2024; Jaramillo & Chiappe, 2024).

Opportunities and Challenges in Implementation

The integration of AI into STEM science education presents significant pedagogical opportunities. AI tools offer real-time feedback, support differentiated instruction, and help personalize content delivery to meet diverse learner needs (Kunnath & Botes, 2025; Rehman et al., 2024). Through intelligent simulations, neural networks, and natural language processing systems, AI enables students to visualize abstract scientific phenomena, perform virtual experiments, and develop computational thinking (Kavitha & Joshith, 2024; Yadav et al., 2016). These benefits align well with 21st-century education goals.

Additionally, AI enhances project-based learning environments by allowing dynamic scaffolding and collaborative knowledge construction. For example, AI tutors can guide students through problem-solving sequences while identifying misconceptions and providing tailored resources (Ruiz Viruel et al., 2025). This facilitates deeper engagement, autonomy, and iterative learning—cornerstones of inquiry-driven STEM education. Furthermore, educational dashboards powered by AI allow teachers to monitor progress and intervene proactively.

Despite these strengths, challenges remain. One major barrier is the lack of teacher preparedness and confidence in using AI tools pedagogically (Ngongpah & Oni, 2025). Many educators lack the technological fluency and pedagogical strategies required to integrate AI meaningfully into classroom practice. Moreover, infrastructural limitations such as unreliable internet access, limited hardware, and digital inequality create substantial implementation gaps—especially in rural or under-resourced schools (Casal Otero et al., 2023; Heeg & Avraamidou, 2023).

Ethical and privacy concerns also limit adoption. Algorithmic biases, opaque decision-making, and data collection practices raise questions about student agency and equity (Jaramillo & Chiappe, 2024; Zhai, 2024). There is a pressing need to develop ethical frameworks that ensure transparency, safeguard learner rights, and foster responsible AI use. Finally, AI integration may inadvertently shift focus from pedagogical intentionality to technological novelty if not guided by clear instructional goals and curricular alignment (Bozkurt, 2023).

Table 3

Opportunities and Challenges in AI-Enhanced STEM Education

Opportunities	**Challenges**
Personalized, adaptive learning	Teacher readiness and confidence gaps
Visualization of complex scientific concepts	Infrastructure limitations in under-resourced settings
Data-driven instruction and feedback	Ethical concerns: privacy, algorithmic bias, transparency
Real-time progress monitoring	Pedagogical misalignment and overreliance on technology
Enhanced project-based and collaborative tasks	Uneven access and digital divides across geographic regions

Synthesis of Key Findings and Gaps

The literature reveals several converging insights and persistent gaps in AI-integrated STEM education. First, AI has demonstrated strong potential to transform science teaching through personalization, engagement, and inquiry-driven learning. Yet this potential is unevenly realized due to infrastructural, pedagogical, and ethical challenges (Huang et al., 2023; Holmes et al., 2019).

A clear finding is the central role of teachers. While AI tools are advancing, their effectiveness hinges on teachers' capacity to adapt them to student needs. However, a

shortage of sustained, practice-based professional development hinders scalable impact (McDaniel, 2025; Mishra & Mehta, 2017). Additionally, the global literature remains skewed toward high-income regions, with limited representation of local innovations in the Global South (Valenzuela, 2025; Bozkurt, 2023).

Research also points to an underdeveloped ethical dimension. Data privacy, algorithmic transparency, and equity remain under-researched, particularly in school settings where student protection is paramount (Jaramillo & Chiappe, 2024; Zhai, 2024). Moreover, few longitudinal studies evaluate the enduring learning outcomes of AI integration, and even fewer explore how AI supports diverse learners (Heeg & Avraamidou, 2023).

Table 4

Synthesis of Reviewed Literature

Key Strengths Identified	Key Gaps and Needs
AI supports personalization and engagement	Lack of teacher training models for AI integration
Strong global policy trends in some regions	Insufficient ethical guidelines in educational AI use
Alignment with 21st-century skill goals	Scarcity of research from Global South and lower-income areas
Promising tools for project-based learning	Absence of longitudinal and inclusive studies

Notwithstanding the burgeoning scholarly interest in AI-integrated STEM education, several critical research lacunae continue to impede the field's systemic development. A primary concern is the pronounced deficiency in sustained, practice-oriented professional development for educators, which serves as a significant barrier to the scalable and efficacious implementation of artificial intelligence tools. This issue is further exacerbated by a notable geographical imbalance in the existing literature, which remains disproportionately concentrated in high-income regions, leaving the unique innovations and pedagogical needs of the Global South largely unaddressed.

Furthermore, the field faces substantial ethical and regulatory voids, particularly regarding data privacy, algorithmic transparency, and equity in primary and secondary school settings. These challenges are compounded by methodological limitations, including a paucity of longitudinal studies to evaluate enduring learning outcomes and a lack of inclusive research focused on diverse learner populations. Consequently, bridging these multidimensional gaps is essential for establishing an equitable and pedagogically grounded framework for AI adoption in science education.

In conclusion, while the global interest in AI-STEM integration is rapidly expanding, the research base remains incomplete and uneven. There is a growing need for contextually grounded, equity-oriented, and pedagogically meaningful approaches to AI adoption in science education. Bridging the divide between innovation and accessibility will be key to ensuring that AI truly serves as a transformative force across diverse educational landscapes.

Conclusion, Discussion and Implications

Implications for Science Curriculum Design

The integration of artificial intelligence (AI) into science education necessitates a reconfiguration of traditional curricular structures to better align with the evolving demands of STEM learning in the 21st century. Science curricula, which have historically been designed around static content delivery and standardized assessments, must now accommodate dynamic, technology-enhanced instructional models that promote inquiry, collaboration, and real-world problem-solving (Huang et al., 2023; Holmes et al., 2019). As AI tools increasingly become part of the learning environment, curriculum designers must consider how these technologies can support pedagogical goals without undermining disciplinary integrity.

A major implication of AI integration is the need for curricular frameworks that embed computational thinking, data literacy, and ethical reasoning across science topics. For instance, the inclusion of AI-powered simulations, virtual labs, and intelligent feedback systems requires the development of new learning objectives and assessment methods that go beyond rote knowledge (Yadav et al., 2016; Zhai, 2024). Project-based modules, supported by AI tutors or adaptive platforms, should be systematically incorporated into curricula to foster higher-order thinking and personalized learning pathways (Rehman et al., 2024).

Curricula must also be flexible and modular to adapt to rapid technological advancements. Traditional linear structures should give way to competency-based progressions, allowing students to demonstrate mastery through diverse AI-enabled activities and formative assessment tools (McDaniel, 2025; Kavitha & Joshith, 2024). In this regard, curriculum designers should collaborate closely with AI developers, educators, and policymakers to ensure that science content remains relevant, inclusive, and accessible.

The table below illustrates essential design shifts required in science curricula to accommodate AI integration:

Table 5

Curricular Shifts in AI-Integrated Science Education

Traditional Curriculum Model	AI-Integrated Curriculum Design
Content-focused, linear sequence	Competency-based, modular structure
Standardized assessments	Adaptive, real-time feedback and performance analytics
Teacher-centered delivery	Student-centered, AI-assisted inquiry learning
Isolated subject focus	Interdisciplinary, problem-based STEM applications
Limited use of technology	Embedded AI tools, simulations, and intelligent systems

As science education increasingly embraces AI, it is essential to safeguard pedagogical intentionality. Technology should enhance—not dictate—learning processes. Thus, the challenge lies in designing curricula that not only integrate AI meaningfully but also preserve the epistemological foundations and inquiry-based nature of scientific learning (Bozkurt, 2023; Heeg & Avraamidou, 2023).

Reflections on Teacher Readiness and Training

The successful integration of AI tools in science classrooms heavily depends on the capacity and readiness of teachers. While AI technologies can enhance instructional quality, they are not self-sufficient; their educational value is ultimately mediated by the teacher's ability to implement, contextualize, and evaluate their use (Dağıstan & Taşdemir, 2026). Teachers' beliefs, digital competencies, and pedagogical flexibility play pivotal roles in determining whether AI-supported practices will lead to transformative learning or superficial adoption.

Research shows that many teachers feel underprepared to incorporate AI tools into their science instruction due to insufficient training, lack of access to relevant resources, and limited opportunities for hands-on experimentation (Kotsis, 2024; Casal Otero et al., 2023). Furthermore, some educator's express skepticism regarding AI's pedagogical value or express concerns about its ethical and practical implications (Jaramillo & Chiappe, 2024). These perceptions highlight the urgent need for robust, sustained, and practice-oriented professional development programs tailored to AI integration in STEM contexts.

Effective teacher training should extend beyond technical skills and include critical reflection on pedagogical strategies, ethical considerations, and student-centered instructional design (Bozkurt, 2023; Mishra & Mehta, 2017). For instance, training sessions can involve co-designing AI-infused science lessons, using real classroom scenarios, and analyzing student data from AI platforms. Peer learning communities and mentoring models can further support knowledge transfer and sustained implementation (McDaniel, 2025).

The following table summarizes key areas of focus for comprehensive teacher training programs in AI-integrated STEM education:

Table 6

Components of Teacher Readiness in AI-Supported Science Education

Dimension	Description
Digital Literacy	Proficiency with AI tools and platforms
Pedagogical Integration Skills	Ability to align AI use with learning objectives and instructional design
Ethical Awareness	Understanding of privacy, data ethics, and responsible AI usage
Reflective Practice	Continuous self-evaluation and adaptation in AI-enhanced environments
Collaborative Learning Culture	Engagement in peer networks and shared professional development

Ultimately, preparing teachers for AI integration requires systemic planning and institutional support. Universities, ministries of education, and ed-tech providers must work collaboratively to ensure that teacher education and in-service programs remain current and relevant. Without addressing teacher readiness comprehensively, AI initiatives in science education risk becoming fragmented and unsustainable (Kunnath & Botes, 2025).

Future Directions in AI-supported STEM Pedagogy

Looking forward, the evolution of AI-supported STEM pedagogy will be shaped by a combination of technological innovation, research-informed practices, and policy frameworks. One promising direction involves the development of AI systems that not only respond to student inputs but also proactively model scientific reasoning, metacognitive strategies, and collaborative problem-solving (Holmes et al., 2019). Such intelligent agents can support deeper inquiry, scaffold abstract thinking, and offer context-sensitive guidance, particularly in complex STEM domains.

Another emerging trend is the convergence of AI with augmented reality (AR), virtual reality (VR), and gamified learning platforms to create immersive science learning environments. These multimodal systems can simulate scientific phenomena, visualize data processes, and allow learners to manipulate virtual variables in real time (Huang et al., 2023; Wang et al., 2024). When grounded in strong pedagogical frameworks, these innovations can enhance engagement, motivation, and scientific literacy.

Furthermore, future pedagogical models must center equity and inclusion. AI systems should be designed to accommodate diverse learning needs, cultural contexts, and linguistic backgrounds. Adaptive platforms must avoid reinforcing biases or standardizing learning paths in ways that marginalize underrepresented students (Casal Otero et al., 2023; Jaramillo & Chiappe, 2024). Therefore, educators and developers must co-design AI tools that reflect the lived experiences and values of the communities they serve.

To support the sustainable evolution of AI-supported STEM pedagogy, research efforts should focus on longitudinal studies that examine long-term learning outcomes, student identity development, and classroom dynamics in AI-mediated environments (Zhai, 2024; Ruiz Viruel et al., 2025). Policy initiatives must promote ethical guidelines, open access to AI technologies, and shared accountability among stakeholders.

Table 7

Strategic Priorities for the Future of AI-Supported STEM Pedagogy

Priority Area	Future Direction
Intelligent Tutoring	Context-sensitive AI agents supporting scientific inquiry and problem-solving
Immersive Learning Technologies	AR/VR-enhanced simulations for real-world scientific exploration
Ethical Design and Equity	Bias-free, inclusive, and transparent AI systems
Longitudinal Research	Empirical studies on impact, identity, and educational equity
Interdisciplinary Collaboration	Joint efforts among educators, developers, and policymakers

In conclusion, the transformative potential of AI in STEM pedagogy lies not in replacing teachers or standardizing learning, but in amplifying the power of inquiry,

personalization, and critical thinking. By aligning technological advancements with ethical and pedagogical commitments, science education can harness AI to cultivate empowered, curious, and future-ready learners.

Conclusion and Recommendations

Summary of the Review

The present literature-based study has explored the intersection of artificial intelligence and STEM-based science education, with a particular focus on how AI technologies are reshaping teaching practices, curriculum structures, and student learning experiences in the 21st century. Through a comprehensive review of global and national trends, it became evident that AI is gradually becoming an indispensable tool in modern science instruction. From adaptive learning platforms to intelligent tutoring systems, AI offers a wide array of pedagogical benefits including personalization, feedback automation, inquiry-based scaffolding, and data-informed instructional decision-making.

The comparative analysis of international and national implementations highlighted a critical divide in the readiness and capability of educational systems to adopt and scale AI integration. While countries with strong digital infrastructure and strategic policies have advanced considerably, others remain in preliminary phases of experimentation. Despite these disparities, a growing consensus exists on the importance of embedding AI tools into science education to foster 21st-century competencies, such as computational thinking, creativity, collaboration, and digital literacy.

Moreover, the review underscored the pivotal role of teachers in the success or failure of AI-enhanced pedagogies. Teacher readiness, professional development, and institutional support emerged as determining factors in effective AI integration. Ethical and infrastructural challenges, including data privacy, algorithmic bias, and unequal access to technology, were identified as ongoing concerns that require urgent attention. Although substantial progress has been made, the literature still reveals significant gaps in empirical research, long-term evaluation, and inclusive pedagogical design.

Strategic Suggestions for Policy and Practice

To bridge the gap between technological innovation and meaningful pedagogical application, several strategic directions for policy and practice can be outlined. First, educational policymakers must prioritize the development of national AI-in-education frameworks that outline ethical, pedagogical, and infrastructural standards. These frameworks should serve as guiding documents for curriculum reform, teacher training, and resource allocation, ensuring that AI integration aligns with educational goals rather than market-driven imperatives.

Second, targeted investments in teacher training are essential. Policymakers should support the creation of professional development programs that are not only technically oriented but also pedagogically grounded. These programs must enable teachers to critically evaluate AI tools, adapt them to their instructional needs, and engage in reflective practices. Partnerships with universities and educational technology

providers can facilitate the co-creation of such training modules and promote sustainability.

Third, AI integration should be embedded into curriculum standards through the adoption of competency-based learning models. These models should emphasize interdisciplinary problem-solving, data interpretation, and scientific inquiry. Schools should be encouraged to experiment with modular course structures that include AI-supported project-based units, virtual experiments, and collaborative design challenges. Such innovations can enhance student motivation while supporting diverse learning pathways.

Finally, equity considerations must remain at the center of implementation strategies. Policies should aim to reduce digital divides by ensuring that all schools—particularly those in under-resourced or rural areas—have access to the infrastructure and technical support required for AI integration. At the same time, ongoing monitoring mechanisms should be established to assess the impact of AI on student outcomes, teacher practices, and educational equity.

Directions for Future Theoretical and Applied Research

The future of AI-supported STEM education will greatly benefit from rigorous theoretical and applied research. Scholars should aim to move beyond surface-level explorations of AI tools and delve into the underlying learning mechanisms they influence. There is a pressing need for frameworks that articulate how AI affects cognitive, emotional, and social dimensions of learning in science classrooms. Such theories can inform instructional design and guide the development of more effective AI applications.

Applied research should focus on longitudinal and mixed-method studies that evaluate the sustained impact of AI tools on academic performance, student engagement, and identity development. These studies should include diverse populations and educational contexts to ensure that findings are generalizable and inclusive. Moreover, future investigations should explore how AI can support students with learning differences, multilingual learners, and those from marginalized communities.

Another promising direction involves design-based research approaches that position teachers, students, and developers as co-researchers in the iterative creation of AI-enhanced learning environments. By fostering participatory methodologies, researchers can ensure that AI tools are contextually relevant, pedagogically sound, and ethically designed. In addition, research should examine policy implications, including how educational systems can govern the use of AI responsibly while fostering innovation.

In conclusion, while AI holds transformative potential for science education, its effective integration requires coordinated efforts across research, policy, and practice. A future-oriented research agenda—anchored in theory, committed to equity, and responsive to classroom realities—will be instrumental in realizing the educational promise of artificial intelligence in STEM learning.

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Statement of Responsibility

This study is single-authored. The author is responsible for the study.

Conflicts of Interest

There is no financial, commercial, or legal interest involved in this study.

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References

Abuhassna, H., Adnan, M. A. B. M., & Awae, F. (2024). Exploring the synergy between instructional design models and learning theories: A systematic literature review. *Contemporary Educational Technology, 16*, ep499. https://doi.org/10.30935/cedtech/14355

Amjad, A., Kordel, P., & Fernandes, G. (2023). The systematic review in the field of management sciences. *Scientific Papers of Silesian University of Technology. Organization and Management Series*. https://dx.doi.org/10.29119/1641-3466.2023.170.1

Belur, J., Tompson, L., Thornton, A., & Simon, M. (2021). Interrater reliability in systematic review methodology: Exploring variation in coder decision-making. *Sociological Methods & Research, 50*(3), 837–865. https://doi.org/10.1177/0049124118799372

Bond, M., et al. (2024). A meta systematic review of artificial intelligence in higher education: A call for increased ethics, collaboration, and rigour. *International Journal of Educational Technology in Higher Education*. https://doi.org/10.1186/s41239-023-00436-z

Bozkurt, A. (2023). Generative Artificial Intelligence (AI) Powered Conversational Educational Agents: The Inevitable Paradigm Shift. *Asian Journal of Distance Education, 18*, 198-204. https://doi.org/10.5281/zenodo.7716416

Casal Otero, Lorena., Catala, Alejandro., Fernández Morante, Carmen., Taboada, Maria., López, Beatriz., & Barro, Senén. (2023). AI literacy in K-12: a systematic literature review. *International Journal of STEM Education. 10*. https://doi.org/10.1186/s40594-023-00418-7

Çelik, İ., Gedrimiene, E., Siklander, P., & Muukkonen, H. (2024). The affordances of artificial intelligence-based tools for supporting 21st-century skills: A systematic review of empirical research in higher education. *Australasian Journal of Educational Technology, 40*. https://doi.org/10.14742/ajet.9069

Dağıstan, A., & Taşdemir, M. (2026). Teachers' opinions on artificial intelligence tools used in education (The case of Kırşehir). *Journal of Theory and Practice in Education, 22*(1), 16-33. https://doi.org/10.17244/eku.1733017

Haryani, E., Cobern, W. W., Pleasants, B. A. S., & Fetters, M. K. (2021). Analysis of teachers' resources for integrating the skills of creativity and innovation, critical thinking and problem solving, collaboration, and communication in science classrooms. *Jurnal Pendidikan IPA Indonesia, 10*, 92–102. https://doi.org/10.15294/jpii.v10i1.27210

Heeg, D. M., & Avraamidou, L. (2023). *The use of Artificial intelligence in school science: A systematic literature review*. *Educational Media International, 60*(2), 125–150. https://doi.org/10.1080/09523987.2023.2264990

Heilala, J., Shibani, A., & de Freitas, A. G. (2023). The requirements for heutagogical attunement within STEAM education. In *Proceedings of the 15th International Conference on Computer Supported Education* (Vol. 1, pp. 461–468). https://doi.org/10.5220/0011964100003470

Holmes, W., Bialik, M., & Fadel, C. (2019). *Artificial intelligence in education: Promises and implications for teaching and learning*. Center for Curriculum Redesign.

Huang, X., Zou, D., Cheng, G., Chen, X., & Xie, H. (2023). Trends, research issues and applications of artificial intelligence in language education. *Journal of Educational Technology & Society, 26*(1), 112–131. https://doi.org/10.30191/ETS.202301_26(1).0009

Jaramillo, J. J., & Chiappe, A. (2024). The AI-driven classroom: A review of 21st century curriculum trends. *Prospects, 54, 645–660. https://doi.org/10.1007/s11125-024-09704-w*

Kavitha, K., & Joshith, V. P. (2024). Artificial Intelligence Powered Pedagogy: Unveiling Higher Educators Acceptance with Extended TAM. *Journal of University Teaching and Learning Practice. https://doi.org/10.53761/s1pkk784*

Khoza, N. G., & van der Walt, F. (2025). *A systematic review on AI-enhanced pedagogies in higher education in the Global South*. *Frontiers in Education, 10*, Article 1667884. https://doi.org/10.3389/feduc.2025.1667884

Kesgin, K. (2025). *Bibliometric analysis and predictive modeling map the role of artificial intelligence in science education from research trends to classroom integration*. *Discover Education, 4*, Article 464. https://doi.org/10.1007/s44217-025-00906-8

Kotsis, K. T. (2024). *Integration of artificial intelligence in science teaching in primary education: Applications for teachers*. *European Journal of Contemporary Education and E-Learning, 2*(3), 27–43. https://doi.org/10.59324/ejceel.2024.2(3).04

Kunnath, A. J., & Botes, W. (2025). *Transforming science education with artificial intelligence: Enhancing inquiry-based learning and critical thinking in South African science classrooms*. *Eurasia Journal of Mathematics, Science and Technology Education, 21*(6), Article em2655. https://doi.org/10.29333/ejmste/16532

McDaniel, A. (2025). Integrating artificial intelligence in STEM education: Enhancing learning through smart technologies. *American Journal of STEM Education, 7*, 1-10. https://doi.org/10.32674/6s0qz548

Mıhladız Turhan, G., & Demirci, I.A. (2021). What are the 21st-century skills for pre-service science and mathematics teachers: Discussion in the context of defined 21st-century skills, self-skills and education curricula. *Journal of Educational Issues, 7*(1), 92-112. https://doi.org/10.5296/jei.v7i1.18278

Mishra, P., & Mehta, R. (2017). *What we educators get wrong about 21st-century learning: Results of a survey*. *Journal of Digital Learning in Teacher Education, 33*(1), 6–19. https://doi.org/10.1080/21532974.2016.1242392

Ngongpah, G., & Oni, O. Y. (2025). *Teachers' readiness and competency in using AI in the classroom*. *Asian Journal of Education and Social Studies, 51*(9), 742–757. https://doi.org/10.9734/AJESS/2025/v51i92412

Ng, D. T. K., Lee, M., Tan, R. J. Y., Hu, X., Tsang, J. S. H., & Chu, S. K. W. (2023). A review of AI teaching and learning from 2000 to 2020. *Education and Information Technologies, 28*, 8445–8501. https://doi.org/10.1007/s10639-022-11491-w

Ng, D. T. K., Leung, J. K. L., Su, J., Ng, R. C. W., & Chu, S. K. W. (2023). Teachers' AI digital competencies and twenty-first century skills in the post-pandemic world. *Educational Technology Research and Development, 71*(1), 137–161. https://doi.org/10.1007/s11423-023-10203-6

Ouyang, F., Dinh, T.A. & Xu, W. (2023). A Systematic Review of AI-Driven Educational Assessment in STEM Education. *Journal for STEM Educ Res 6*, 408–426. https://doi.org/10.1007/s41979-023-00112-x

Öztürk, B. (2023). The effect of cooperative learning models on learning outcomes: A second-order meta-analysis. *Educational Policy Analysis and Strategic Research, 18*, 273-296. https://doi.org/10.29329/epasr.2023.600.13

Pejić Bach, M., & Cerpa, N. (2018). Editorial: Planning, conducting and communicating systematic literature reviews. *Journal of Theoretical and Applied Electronic Commerce Research, 14, I–IV. https://doi.org/10.4067/S0718-18762019000300101*

Rehman, N., Huang, X., Mahmood, A., AlGerafi, M. A. M., & Javed, S. (2024). *Project-based learning as a catalyst for 21st-century skills and student engagement in the math classroom*. *Heliyon, 10*(23), e39988. https://doi.org/10.1016/j.heliyon.2024.e39988

Ruiz Viruel, S., Sánchez Rivas, E., & Ruiz Palmero, J. (2025). *The role of artificial intelligence in project-based learning: Teacher perceptions and pedagogical implications*. *Education Sciences, 15*(2), 150. https://doi.org/10.3390/educsci15020150

Sánchez Serrano, S., Pedraza Navarro, I., & Donoso González, M. (2022). ¿Cómo hacer una revisión sistemática siguiendo el protocolo PRISMA? Usos y estrategias fundamentales para su aplicación en el ámbito educativo a través de un caso práctico. *Bordón. Revista de Pedagogía, 74*(3), 51-66. https://doi.org/10.13042/Bordon.2022.95090

Shams, R. A., Zowghi, D., & Bano, M. (2023). *AI and the quest for diversity and inclusion: A systematic literature review*. *AI and Ethics, 5*, 411–438. https://doi.org/10.1007/s43681-023-00362-w

Sohrabi, C., Franchi, T., Mathew, G., Kerwan, A., Nicola, M., Griffin, M., Agha, M., & Agha, R. (2021). PRISMA 2020 statement: What's new and the importance of reporting guidelines. *International Journal of Surgery*, *88*, 105918. https://doi.org/10.1016/j.ijsu.2021.105918

Strong, M. H., Burkholder, G. J., Solberg, E. G., Stellmack, A., Presson, W. D., & Seitz, J.-B. (2020). *Development and validation of a global competency framework for preparing new graduates for early career professional roles*. *Higher Learning Research Communications, 10*(2), 67–115. https://doi.org/10.18870/hlrc.v10i2.1205

Valenzuela, J. (2025). Using AI tools to support project-based learning. *Edutopia*. https://www.edutopia.org

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*(Part A), Article 124167. https://doi.org/10.1016/j.eswa.2024.124167

Yadav, A., Hong, H., & Stephenson, C. (2016). *Computational thinking for all: Pedagogical approaches to embedding 21st century problem solving in K–12 classrooms*. *TechTrends, 60*(6), 565–568. https://doi.org/10.1007/s11528-016-0087-7

Zawacki-Richter, O., Marín, V. I., Bond, M., & Gouverneur, F. (2019). Systematic review of research on artificial intelligence applications in higher education – where are the educators? *International Journal of Educational Technology in Higher Education, 16*. https://doi.org/10.1186/s41239-019-0171-0

Zhai, X. (2024). AI and machine learning for next generation science assessments. *arXiv*. https://arxiv.org/abs/2405.06660

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