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AI-Enhanced STEM Education: Emerging Trends, Innovations, and Challenges

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Abstract. This systematic review explores the application of artificial intelligence in STEM education through the analysis of 29 peer-reviewed articles, following the PRISMA methodology. The main research questions include (i) problems that arise when integrating artificial intelligence into STEM education systems, (ii) changes in AI-assisted STEM teaching compared to traditional methods, and (iii) the impact of teachers' ICT competencies and professional development on the application of AI in STEM education. The results indicate the pedagogical, ethical, and technical challenges that artificial intelligence brings as systemic solutions to complex mutual challenges. Among the most prominent pedagogical problems is students' overdependence on AI as a problem-solving resource. Ethical concerns include the protection of privacy and data, as well as the inherent biases of algorithms. Improving learning and increasing student engagement with AI tools depends on their prior knowledge. The last section of the paper underlines the need for institutional dedication to ongoing professional growth in order to support the dynamic integration of artificial intelligence in education.

Keywords: STEM Education; Artificial Intelligence in Education; STEM Education Evolution.

1. Introduction

The twenty-first century has witnessed an inexorable evolution of artificial intelligence (AI) driven by its widespread adoption across various sectors. AI is a broad concept that encompasses various computational tools and methodologies designed to replicate human cognitive functions, enabling machines to perform tasks typically requiring human intelligence. With the ability to access and analyse vast amounts of digital information, AI technologies are increasingly embedded in everyday life. A growing number of devices, employing advanced techniques such as deep learning, could provide intelligent services by reasoning and behaving in human-like ways.

In the educational context, AI has the potential to complement, and in some scenarios even replace, certain roles of educators and support staff in schools. Experts anticipate

that AI adoption across domains will increase operational efficiency, reduce costs, and enhance user experience. As a result, AI is transforming fundamental aspects of human life, including work, education, and everyday experiences. In education, AI serves diverse purposes for different stakeholders. While students primarily use AI to support learning and assignments, academics also employ AI tools for research, curriculum development, and administrative tasks. The motivations and applications vary, reflecting a broader shift in educational practices enabled by intelligent technologies.

The evolution of digital technologies and computer science is ushering in a new era, a technologically driven society in which machines are increasingly designed to serve human needs, while simultaneously growing in complexity and capability.

Education is among the sectors most profoundly affected by AI. Its influence is evident in several domains, including personalised learning platforms that adapt to students' needs and pacing, as well as automated grading systems that allow instructors to dedicate more time to meaningful engagement with students [6,19]. Intelligent tutoring systems provide tailored assistance and feedback, diagnose learning gaps, and provide customized remediation [30,31]. Moreover, AI-driven systems may scrutinize extensive educational data to discern trends and patterns, therefore guiding curriculum creation and instructional tactics. Chatbots are progressively used to provide immediate responses to student inquiries, providing round-the-clock assistance and advice.

However, the incorporation of AI in education raises significant ethical concerns, including data privacy, algorithmic prejudice, and the potential marginalization of human educators. To harness AI's benefits while mitigating its risks, careful design and implementation are essential. This ensures that AI complements and enhances the role of human educators in shaping the future of education, rather than diminishing it.

In the context of STEM (science, technology, engineering, and mathematics) education, AI plays a transformative role. It enables personalised learning through interactive simulations, gamified environments, and real-time analytics [54]. By leveraging open educational resources and digital platforms, AI promotes critical thinking, problem-solving, and enthusiasm for STEM fields, equipping students with the skills necessary for future careers [38].

Furthermore, AI-powered tools offer adaptive assessments that identify knowledge gaps, enabling educators to provide targeted interventions and personalised feedback. This approach moves education beyond traditional rote memorization, fostering a deeper understanding of STEM concepts and encouraging students to explore their interests. By providing access to vast databases of scientific information and research, AI also empowers students to conduct independent investigations and contribute to real-world problem-solving. As STEM education continues to evolve, AI stands out as a driving force that not only optimizes learning outcomes but also equips students with the digital literacy and adaptability required to succeed in an increasingly technology-dependent world. Through continuous refinement, AI promises to revolutionize STEM education, ensuring a future workforce that is both knowledgeable and innovative.

This systematic review aims to identify trends, innovations, and challenges in AI-supported STEM education. This study follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology [36] to ensure a rigorous and transparent review process.

The remainder of this article is organised as follows. Following the introduction, the second section presents trends, innovations, and challenges in AI-enhanced STEM education, providing a conceptual and theoretical background based on recent literature, and concludes by outlining the research questions that guide the systematic review. The third section describes the research methodology, including the PRISMA-based search strategy, inclusion and exclusion criteria, data screening, and quality assessment procedures. The fourth section presents the results of the review, structured according to the three research questions. The fifth section discusses the findings in relation to existing literature and highlights their pedagogical, ethical, and practical implications. Finally, the sixth section concludes the article by summarising its main insights, outlining its limitations, and suggesting directions for future research.

2. Trends, Innovations, and Challenges in AI-Enhanced STEM Education

Artificial Intelligence in Education (AIEd) is an emerging field dedicated to leveraging AI technologies to achieve diverse educational objectives. Its primary aim is to transform, enhance, and simplify teaching and learning processes. A key area within AIEd is the improvement of STEM education at all levels, from early childhood to postgraduate studies. By implementing AI technologies, AIEd strives to increase student achievement in STEM subjects across various educational systems [58].

The integration of AI into pedagogical practices holds transformative potential, bridging the gap between rapid technological advancements and the sociocultural dimensions of learning. AI's capacity to personalise instruction based on individual student needs presents unprecedented opportunities for tailored education. This fosters dynamic learning environments where content and progression are aligned with each student's unique strengths, weaknesses, and preferred learning styles.

Researchers such as [56,50,28] highlight AI's potential to revolutionize education by transforming learning processes, instructional delivery, outcome reporting, and even automating administrative tasks. AI's autonomous capacity to adjust instruction benefits both students and teachers [26]. Traditional teaching approaches often fail to accommodate students' diverse learning preferences and paces, tending to address an imagined "average student" while overlooking individual differences[52].

AI-powered adaptive learning systems can capture and process data to adjust course content, volume, and difficulty, along with the pace of instruction, while providing real-time, personalised feedback [21]. Personalization is believed to enhance engagement, motivation, and achievement [50], ultimately reducing achievement gaps and promoting equity by providing access to individualized instruction [58]. Furthermore, AI facilitates increased student engagement and participation through immersive and interactive activities. Virtual instructors and AI-powered chatbots enable personalised support through conversational interfaces, answering questions and offering guidance in real time [28]. This interactive format of learning improves students' self-efficacy, motivation, academic persistence, and self-regulated learning.

One of the major advantages of AI in STEM higher education lies in its ability to deliver customized and flexible learning experiences. By assessing student performance, preferences, and learning styles, AI-driven educational systems can tailor instruc-

tion to individual needs. This facilitates deeper comprehension of complex STEM concepts through targeted pacing, content, and intensity. The effectiveness of AI-enhanced instruction in higher education largely depends on this level of personalization and adaptability [21]. STEM educators, who often face the challenges of conveying complex disciplinary concepts, may find that AI technologies can alleviate some of their workload [55]. Consequently, driven by the synergistic combination of technology and innovation within STEM fields, there has been a notable increase in literature reviews and bibliometric analysis exploring the intersection of AI with STEM education [16], science education [27], and mathematics education [11,21,33]. While the AI applications in education are profoundly evolving the sector, it also introduces critical ethical concerns. These include the redefinition of instructional practices and learning standards, as well as ethical responsibility for outcomes [2,7,9,5].

The implementation of AI technology in the educational realm shifts the ethical responsibility of the educators, which, in turn, requires a revision of long-standing educational norms and responsibilities, previously settled guidelines and obligations. Preventive strategies, such as embedding ethics into curricula and acknowledging the limitations and biases of AI systems, are essential for the development of accountable and transparent AI. Ethical concerns extend beyond technical considerations and must encompass broader societal issues, such as data privacy, social justice, and equity [2].

Adopting AI technologies in educational institutions and practices presents both opportunities and challenges. One key concern is how AI tools or intelligent tutoring systems, are integrated within specific STEM domains. Another important issue is the ability of students to critically evaluate the accuracy and completeness of AI-provided feedback. Research studies show that students with insufficient prior knowledge in a given STEM area may blindly accept AI answers, which is a quintessentially AIEd problem. Passive learning patterns further exacerbate this issue, as many students engage with AI tools without questioning their validity.

The effectiveness and accuracy of AI feedback also depend on factors such as task's complexity and the input information's quality, as well as instructional clarity [28]. Additionally, excessive reliance on AI may impair the development of core skills, such as problem-solving, critical thinking, intrinsic motivation, collaborative work, and engagement in learning activities [12,22,31,38]. In addressing these challenges, educators should take proactive steps to mitigate students' overreliance on AI tools by establishing clear guidelines and promoting responsible use within the classroom.

The challenges associated with implementing AI technologies in education also extend to the agencies responsible for developing educational content, teacher training programs, and the necessary technical infrastructure. Scalability and equity are among the key issues faced by these non-profit government entities. Without a deliberate focus on pedagogy, the deployment of AI tools may reinforce rather than reduce existing disparities. For example, AI-based assessment tools may disadvantage students in under-resourced settings who lack access to devices, internet connectivity, or digital literacy skills [47]. Another challenge lies in the "black box" nature of certain AI algorithms, which limits transparency and accountability. Developers of educational content must consider how these systems align with learning objectives, uphold equity, and ensure algorithmic fairness. Educators must be trained not only to operate AI tools but also to understand their underlying logic, limitations, and ethical implications. This shift requires

a reorientation from tool mastery toward critical understanding of AI's foundational principles and biases.

Also, the rapid evolution of AI tools is significantly reshaping educational environments, creating both advantages and limitations for teachers and students. Generative AI technologies have entered classrooms at a remarkable pace, often exceeding the ability of curricula and institutional policies to adapt. This accelerated adoption places increasing demands on educators to modify instructional practices while maintaining professional autonomy. In light of this, teacher education needs to move beyond basic technical training and emphasise critical thinking and ethical engagement with AI, while policy frameworks should support collaborative approaches that position teachers as active partners in AI integration design rather than as passive implementers of externally imposed decisions [51]. At the same time, students are integrating AI tools into their learning practices faster than expected, raising concerns related to equity, preparedness, and the sustainability of instructional strategies [18]. The expanding AI tools market further amplifies these dynamics, underscoring the need for continuous professional development and systemic support to ensure that rapid innovation leads to effective educational outcomes [59].

In addition, the ethical dimensions of data privacy and security represent fundamental challenges for institutions implementing AI in education. Higher education institutions must implement robust access controls and protections against unauthorized use of student data. Building trust with students requires clearly defined ethical boundaries for AI deployment in educational contexts.

Finally, technical requirements cannot be overlooked [19]. Effective AI integration depends on reliable digital infrastructure, stable internet connectivity, and ongoing technical support. Even the most sophisticated AIs solutions cannot meet expectations without these essential components. The following section presents a comprehensive overview of the challenges faced by students, teachers, and institutions in implementing AI within STEM education (Table 1).

The integration of AI tools such as ChatGPT alongside traditional teaching methods fosters a productive synergy between educators and technology. As STEM disciplines continue to evolve, it becomes increasingly necessary to update AI models regularly to ensure their pedagogical relevance and effectiveness. Several studies have underscored the need for more comprehensive theoretical approaches to guide the development and implementation of educational chatbots, particularly in the context of robot-assisted learning environments [3,14,49].

In parallel, the increasing relevance of data in educational settings places a stronger emphasis on data literacy and statistical competencies within STEM education, allowing students to make well-informed decisions across numerous disciplines. Moreover, the integration of computational thinking and coding into mathematics instruction equips learners to design algorithms, translate mathematical concepts into programs, and apply technological tools to complex problem-solving thus enhancing their reasoning and analytical abilities. Although tools like ChatGPT offer considerable potential for solving advanced mathematical problems, their outputs must be verified against trusted sources to ensure accuracy and reliability [49].

The effective use of AI technologies in teaching and learning requires an adequate level of digital literacy, such as being capable of evaluating and employing generative AI tools within the framework of academic integrity [28]. For students, this means rec-

Table 1. Challenges of AI integration in STEM education across students, teachers, and institutions

Challenges	Students	Teachers	Institutions
Technical Infrastructure [19]	Lack of access to technology [58]	Limited training in AI tools [28]	Insufficient infrastructure and resources [42]
Access to Training and Support [37,47]	Inadequate training on AI tools [47]	Need for continuous professional development [47]	Lack of funding for training and support [35]
Curriculum Adaptation [26]	Difficulty adapting to new learning methods [37]	Reduced flexibility in lesson planning [26]	Need for curriculum and syllabus revisions [47]
Understanding and Interpreting Data [38]	Struggles in understanding complex AI tools [14]	Challenges in interpreting AI-generated data [14]	Issues with assessing the accuracy and relevance of data [38]
Engagement and Motivation [50]	Lack of motivation due to complexity [52]	Difficulty tracking student progress in real time [2]	Low interest in AI implementation among students [17]
Ethics and Privacy [28]	Concerns about data privacy [28]	Identifying and addressing ethical dilemmas in teaching [28]	Maintaining ethical guidelines in AI implementation [38]
Different Rates of Adoption [22]	Variations in the speed of student adaptation [8]	Inequality in access to AI tools [57]	Incomplete development of inclusive strategies [22]

ognizing when AI is being used, assessing the reliability and validity of its content, and considering the broader ethical and social implications of AI applications. Importantly, the increasing use of AI in education raises fundamental questions of equity and access. Biases embedded within AI algorithms and training data must be addressed to prevent the reinforcement of existing inequalities and to ensure that all learners are provided with fair and inclusive educational opportunities [37].

2.1. Research Questions

The objective of this study is to conduct a systematic review of recent trends, challenges, and innovations in AI-driven STEM education, covering the period from 2020 to 2025. Specifically, the study aims to examine how the integration of AI has contributed to the modernization of STEM teaching and learning practices. The following research questions guided the review:

RQ1. What are the key pedagogical, ethical, and technical challenges associated with the integration of AI into STEM education?

RQ2. In what ways are modern AI tools reshaping STEM teaching and learning compared to traditional instructional methods?

RQ3. How can teachers' ICT competencies and professional development influence the successful integration of AI in STEM education, and what challenges do they face in adopting AI-based teaching methods?

3. Research Methodology

A systematic review is designed to answer specific research questions through a clearly defined, methodical, and replicable search strategy. This process involves the application of predetermined inclusion and exclusion criteria to identify relevant studies and exclude those that do not meet the established parameters.

In this study, a comprehensive analysis of relevant literature was conducted following the PRISMA methodology [36]. Figure 1 presents the PRISMA flow diagram illustrating the sequential steps undertaken during the review.

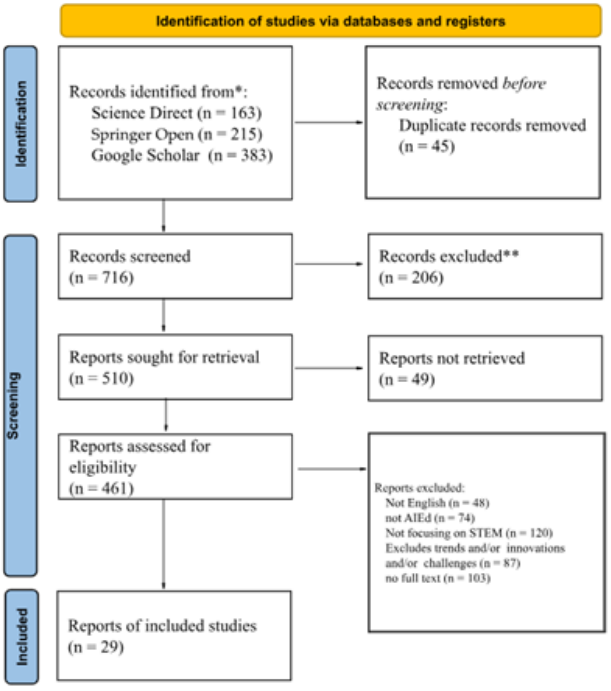


Fig. 1. PRISMA flow diagram of the systematic review

Figure 2 presents the co-authorship network of researchers in the field of AI-enhanced STEM education. This network highlights influential authors and collaborative groups, illustrating how academic alliances contribute to knowledge generation. Each node represents an individual author, while edges denote co-authorship relationships. Densely connected clusters indicate strong research collaborations, reflecting emerging communities of practice and shared research interests.

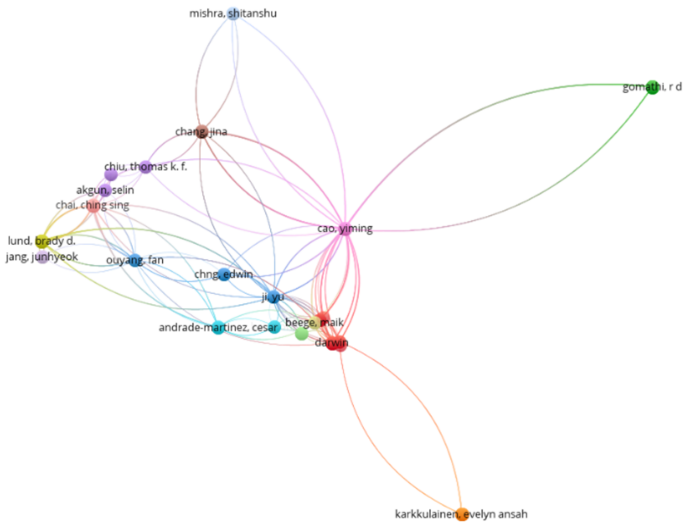


Fig. 2. Co-authorship network

The network exhibits a clear core–periphery structure. A small subset of authors is positioned in the central region of the network, characterised by a high number of co-authorship links and a bridging role between multiple clusters. Within the network representation, colour differentiation is employed to visually separate co-authorship communities, enabling clearer recognition of collaboration patterns. In particular, the red-coloured cluster stands out as one of the more densely connected co-authorship communities. This configuration reflects high degree centrality and indicates that these authors connect several otherwise weakly connected collaborative groups. Peripheral nodes exhibit fewer co-authorship ties and are connected to the broader network primarily through a limited number of links to central or semi-central authors. Overall, the observed co-authorship structure suggests that research in AI-enhanced STEM education is organised around a limited number of highly influential authors acting as collaboration hubs, alongside several well-defined research communities. The presence of inter-cluster connections indicates that several collaborative groups are directly linked through co-authorship relationships.

3.1. Identification of Publication

The identification procedure involved systematic searches across three major academic databases: Science Direct, Springer Open, and Google Scholar. Keywords related to the research topic, including synonyms and related terms, were employed to maximize the yield of potentially suitable publications. Boolean operators (AND or OR) were utilized to refine the search strategies and ensure the retrieved articles aligned with the specific research questions. Search strings were slightly adapted to accommodate the indexing structures and search functionalities of each database. To ensure that only studies that meet the standards of the scientific community were identified, it focused exclusively on peer-reviewed articles and excluded gray literature.

3.2. Screening Phase of the PRISMA Methodology

Considering the diversity of databases and the varying relevance of retrieved publications, each article's abstract was initially reviewed individually to assess its suitability. In the second phase, a more detailed screening was conducted based on predefined criteria outlined in Table 2. Only peer-reviewed journal and conference articles written in English were considered, with a focus on STEM education and related themes such as innovations, trends, and challenges. During the initial screening process, 45 out of 761 articles were excluded due to insufficient relevance or methodological limitations. The selected articles addressed a range of research topics related to STEM education, including science, physics, mathematics, technology, and engineering education, and encompassed empirical studies, comparative and controlled group research, as well as meta-analyses.

Table 2. Inclusion and exclusion criteria used in the systematic review

Criteria	Inclusion	Exclusion
Publication time frame	2020 – 2025	Before 2020
Document type	Journals and conference articles	Dissertations, books, etc.
Language	English	Non-English
Availability	Full-text available (open access or institutional access)	Abstracts without full-text access

The literature search was conducted using Google Scholar, ScienceDirect, and Springer databases, which are widely recognised and frequently used in the field of educational technology. To ensure a comprehensive and methodologically sound data collection process, the search strategy was informed by approaches used in previous systematic reviews and studies examining artificial intelligence and STEM education [58,9,55]. Table 2 outlines the Boolean search criteria applied in this review.

The search strategy was carefully designed and involved the construction of five distinct sets of keywords. Each keyword set corresponded to one of the primary research themes identified in the study. These sets were formulated to capture diverse yet relevant dimensions of the research focus, thereby ensuring a comprehensive and targeted retrieval of pertinent peer-reviewed literature.

Within each keyword group, semantically related terms were combined using the Boolean OR operator to capture variations and synonyms of the same concept. Keywords from different thematic groups were then connected using the Boolean AND operator to ensure that retrieved studies simultaneously addressed multiple dimensions of AI-enhanced STEM education. The use of structured keyword combinations and Boolean operators is consistent with established approaches to systematic literature searching in AI and STEM education research [58,10,9].

The five keyword groups were organised as follows Table 3. Group (A) focused on concepts related to innovations, emerging trends, current challenges, common obstacles, and possible prospects in the field of STEM education. Group (B) included search phrases related to STEM learning environments, covering various aspects of the physical and digital contexts in which STEM education takes place. Terms denoting the core STEM educational disciplines – mathematics, science, technology, and engineering – comprised Group (C). Group (D) contained terms related to pedagogical approaches, AI-supported learning strategies, and technology-enhanced teaching methods specific to STEM educa-

tion. Finally, Group (E) focused on ethical considerations surrounding the use of AI in education, AI-powered tools, and intelligent support systems designed to enhance STEM learning outcomes [58,9,55].

This comprehensive keyword grouping strategy enabled a systematic and targeted literature search aligned with the main research themes, ensuring the inclusion of diverse yet relevant sources across multiple dimensions of AI-enhanced STEM education.

Table 3. Keyword thematic grouping

A	B	C	D	E
Trends	Virtual Labs	Mathematics Education	Computational Thinking	Intelligent Support
Innovation	Collaborative Learning Spaces	Technology Education	AI-Assisted Learning	Artificial Intelligence
Challenges	Laboratory	Science Education	Adaptive Learning Systems	Machine Intelligence
Barriers	Smart Learning Environments	Engineering Education	Problem-Based Learning	AI-driven Tutoring
Opportunities	Makerspaces	STEM Education	Data Literacy in STEM	AI Bias in Learning Systems

Using VOSviewer, Figure 3 demonstrates co-occurrence of keywords in AI-STEM education. The thickness of the links indicates co-occurrence, thus revealing thematic clusters and conceptual connections. The amount of each keyword node indicates the degree of keywords. This network highlights primary STEM education topics, emerging developments, and the interplay of the sociocultural, technological, educational, and ethical dimensions.

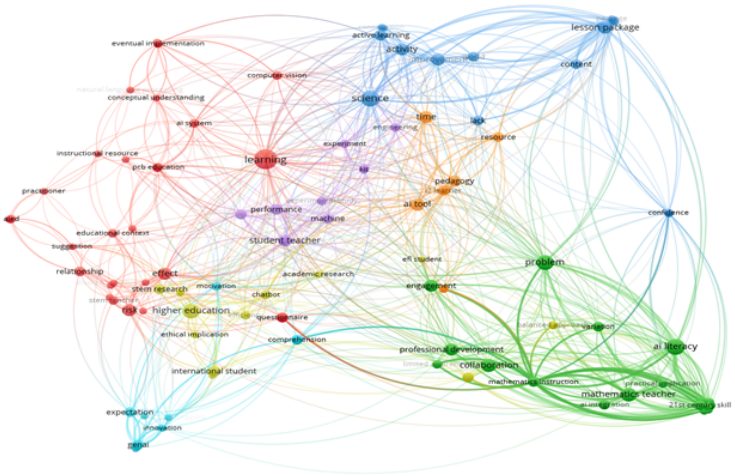


Fig. 3. Keyword co-occurrence network – VOSviewer

3.3. Eligibility and Inclusion in Research

A closer examination of the network reveals several keyword clusters that capture distinct yet interconnected thematic orientations in AI-STEM education research. Frequently occurring keywords such as learning, science, pedagogy, problem, and AI literacy appear across multiple clusters. They are repeatedly linked to a wide range of related terms, indicating their foundational role across multiple research themes and their function as conceptual reference points connecting different lines of AI-STEM education research.

In the network visualization, node colours are used to distinguish clusters of closely associated keywords. In particular, the red cluster groups recurrent terms related to learning processes and educational outcomes, including keywords such as learning, effect, and achievement, pointing to a concentration of studies addressing learning-related and outcome-oriented dimensions. Co-occurrence links between keywords from different clusters indicate that concepts related to learning, pedagogy, AI, and STEM content are frequently examined together, reflecting overlapping thematic boundaries within the analysed literature.

Out of the 716 records initially retrieved, 206 articles were excluded based on relevance and screening criteria, resulting in 510 studies retained for full-text quality assessment (Table 4). The quality assessment process was guided by a set of predefined evaluation criteria designed to assess the methodological and conceptual rigor of each study. Specifically, the following questions were used to determine the inclusion of studies in the final synthesis:

1. **Relevance**: Does the study provide a comprehensive overview of the background, impact, advancements, and challenges associated with AI applications in STEM education?

2. **Clarity of Objectives**: Are the research aims and objectives clearly defined, particularly in relation to the AI techniques or tools being investigated?

3. **Methodological Transparency**: Does the study clearly outline the evaluation approach for AI-enhanced STEM education, including data collection methods, selection of tools, and implementation strategies?

4. **Evidence and Support**: Does the article present well-structured and clearly documented empirical evidence – such as case studies, experimental data, statistical analyses, or comparative assessments?

5. Va**lidation of Findings**: Are the conclusions supported through comparative analysis, triangulation, or other forms of validation that ensure the credibility of the results?

6. **Scope and Generalizability**: Is the scope of the study – including sample size and application context – sufficient to draw meaningful conclusions about the effectiveness and challenges of AI-enhanced STEM education?

Table 4. Criteria for quality assessment of articles

No	Criteria	Descriptions
1	Study context	Does the article effectively present the context of AI applications in STEM education and their impact on innovations, trends, and challenges?
2	Objectives and aims	Are the study's aims and objectives clearly stated, particularly with regard to the role and intelligence of AI-enhanced tools and methodologies in STEM education?
3	Methodology	Does the article comprehensively explain the methodology used for analysing AI-enhanced STEM education, including the selection of AI tools, implementation strategies, and data collection procedures?
4	Validation of results	Does the document provide supporting evidence (e.g., case studies, experimental results, statistical analyses, or comparative evaluations of AI-enhanced versus traditional STEM teaching), and is the information presented clearly and structurally?
5	Sample	Does the study include a sufficient sample size and scope of AI-enhanced STEM applications to enable meaningful conclusions regarding effectiveness and challenges?

With regard to the quality assessment of the included articles, priority was initially given to fulfilling all predefined criteria. These criteria were originally regarded as mandatory for both empirical research studies and systematic meta-analyses. The systematic meta-analyses primarily followed the PRISMA methodology. Nevertheless, to ensure an adequately sized sample and to avoid the exclusion of high-quality studies within the domain, the criteria were not weighted equally. Although a formal weighting formula was not applied, greater importance was assigned to criteria such as Study context, Objectives and aims, and Sample. While this approach ensured consistency in the quality assessment process, it may have introduced potential selection bias by favouring studies that more explicitly contextualise AI applications in STEM education and clearly articulate their objectives and scope, potentially under-representing studies with less explicit contextual framing.

Conversely, criteria related to methodological aspects – encompassing research design, data collection, and analytical techniques – were given comparatively less weight. This decision stemmed from the recognition that methodological rigour within AIEd research can vary significantly depending on the specific AI technology being employed, the educational context, and the research question being addressed. For instance, studies exploring the effectiveness of AI-powered tutoring systems might necessitate different evaluation metrics and research designs compared to studies investigating the use of AI for automated assessment.

Consequently, rigidly enforcing methodological criteria could inadvertently exclude valuable insights from studies adopting innovative or context-specific approaches. Furthermore, the assessment process was sensitive to the interdisciplinary nature of AIEd, acknowledging that the methodological norms and expectations can differ across the fields of AI, education, and STEM disciplines. While striving for methodological transparency and soundness, the quality assessment aimed to avoid imposing a one-size-fits-all approach that might unduly penalise studies adhering to rigorous standards within their

respective fields. It is important to acknowledge that this approach carries the risk of including studies with methodological limitations. Following the systematic review of the literature, 29 relevant studies published between 2020 and March 2025 were identified. These studies were subsequently subjected to content analysis, with a specific focus on the formulation of their research questions and the methodological approaches used to address them (Table 5).

Table 5. Summary of key studies and findings on AI integration in STEM education

Year	Researcher	Findings
2025	Opesemowo, O. A. G. [41]	The study states that AI offers significant potential to improve mathematics education through personalised learning, adaptive assessments, and interactive environments. However, careful integration is crucial, as it addresses ethical concerns, biases, and the continued importance of human educators. A collaborative approach that prioritises transparency, fairness, and collaboration will ensure the responsible and effective use of AI, fostering a dynamic and inclusive learning environment.
2024	Saradha, P., Gomathi, R. D., Mythili, M., Jamuna, G., Karthick, S., Indhumathi, N., and Hariharan, G. [45]	AI tools like chatbots and simulations enhance L2 learners' language skills, critical thinking, and problem-solving through personalised support and increased engagement. While challenges exist in implementation, including teacher training and data privacy, proper integration of AI can significantly improve pedagogy and prepare students for engineering careers.
2024	Joseph, O. B., and Uzondu, N. C. [26]	The study points to the significant potential of artificial intelligence and machine learning to improve STEM education through personalised learning, adaptive tutoring systems, and real-time feedback. Key challenges include ethical issues of data privacy, insufficient teacher training, and the need for adequate technological infrastructure.
2024	Egara, F. O., and Mosimege, M. [13]	This study reveals that mathematics teachers acknowledge ChatGPT's capacity to enhance pedagogical practices through immediate question answering, conceptual clarification, and problem-solving assistance. Nevertheless, effective integration faces obstacles such as insufficient knowledge of artificial intelligence, inadequate professional development for educators, technical constraints, and concerns regarding the reliability and ethical implications of generated responses. To facilitate successful implementation, the study advocates enhanced teacher training programmes, suitable infrastructure, and ethical guidelines governing the use of AI tools in education.

Year	Researcher	Findings
2024	Llerena-Izquierdo, J., Mendez-Reyes, J., Ayala-Carabajo, R., and Andrade-Martinez, C. [34]	The study shows that AI tools such as GenAI Gemini in Google Colab improve students' understanding of programming, motivation, and satisfaction. However, challenges arise in pedagogy, technology, and ethics, especially overreliance. Education requires strategies that effectively integrate AI while preserving critical thinking and problem-solving skills.
2024	Wijaya, T. T., Yu, Q., Cao, Y., He, Y., and Leung, F. K. S. [57]	The study results highlight that while artificial intelligence offers valuable opportunities to improve educational practices, its uncritical adoption may inadvertently hinder the cultivation of independent thinking and key cognitive competencies. Consequently, a thoughtful and strategically informed approach to the application of AI in education is of paramount importance.
2024	Silva, C. A. G. d., Ramos, F. N., de Moraes, R. V., and Santos, E. L. d. [48]	The study explores how integrating ChatGPT into programming classes improves perceived support and understanding but raises ethical concerns, plagiarism risks, and potential dependence on artificial intelligence. A balanced pedagogical approach is key to maximising benefits while fostering independent problem-solving skills.
2024	Ouyang, F., Xu, W. [42]	Educational robotics had a moderate positive effect on STEM learning, particularly improving learning performance and attitudes, while its effect on computational thinking was insignificant. Effects varied significantly by STEM discipline, with stronger outcomes in technology and interdisciplinary contexts.
2024	Selvam, A. A. A. [46]	The research evaluated the impact of AI in physics, chemistry, and biology education and concluded that students' learning experiences have been significantly influenced by AI. Educational resources can be tailored to individual needs, improving learning outcomes and expanding access to learning opportunities. The study also highlights the importance of understanding AI ethics and its associated challenges.
2024	Beege, M., Hug, C., and Nerb, J. [4]	The research focuses on the use of ChatGPT in STEM education from a teacher's perspective. It concludes that ChatGPT is not yet widely used in classrooms, but its use is expected to grow, with teachers' attitudes playing an important role in this development. Despite concerns about potential risks, teachers remain inclined to use ChatGPT, suggesting that its perceived benefits may outweigh its risks.

Year	Researcher	Findings
2024	Mirea, N., Palade, M., and Gaureanu, A. [35]	The article highlights that the integration of artificial intelligence into STEM education offers significant benefits in terms of personalisation and the enhancement of critical thinking. However, it also raises ethical concerns, including algorithmic bias, privacy issues, and accountability. The authors stress the importance of carefully planned and ethically grounded implementation of AI technology to ensure transparency, build trust, and promote the long-term sustainability of education systems.
2024	Li, T., Ji, Y., and Zhan, Z. [33]	The paper examines the impact of student teachers collaborating with experienced teachers and utilising ChatGPT on students' critical thinking, learning performance, and cognitive load within an integrated STEM course. The findings provide insights into how different forms of learning support influence these outcomes.
2024	Ilić, J., Ivanović, M., and Klašnja-Milićević, A. [24]	A review of the literature shows that the use of ChatGPT within higher education STEM courses can improve students' educational experiences by enhancing motivation, aiding comprehension of difficult concepts, and providing tailored learning assistance. However, concerns remain regarding cheating, technological limitations, and insufficient teacher training on the ethical use of AI-based educational tools.
2023	Idil, S. [23]	AI technology implementation requires teachers' pedagogical and digital skills, while educational leaders must address ethical and privacy-related considerations.
2023	Chiu, T. K. F., and Li, Y. [8]	The research indicates that technology applications can enhance science education by supporting personalised feedback and facilitating students' argumentation and reasoning.
2023	Park, J., Teo, T. W., Teo, A., et al. [43]	The study explores AI's emerging role in science education. Teachers recognise the value of AI, but implementation faces several challenges. A gap exists between AI's projected impact and its actual use. Current curricula require modification to address emerging educational needs. Although personalised learning is promising, it also raises ethical and reliability concerns.
2023	Triplett, W. J. [52]	The study confirms the potential of technology in STEM education but finds that classroom use remains limited despite increased access. Teacher proficiency is essential, while inadequate training can hinder effective integration and the full realisation of benefits such as student engagement and improved STEM outcomes. Sustained professional development is therefore crucial.

Year	Researcher	Findings
2023	Wang, T., Lund, B. D., Marengo, A., Pagano, A., Mannuru, N. R., Teel, Z. A., and Pange, J. [56]	This research examines the effects of AI tools, including generative chatbots and analytics, on international students' academic experiences. The authors found that students primarily used AI chatbots to prepare for classes and complete academic tasks, with many modifying the generated output. These tools have the potential to support academic success and enhance students' motivation towards learning.
2023	Triplett, W. J. [53]	The study analyses the challenges of integrating technology into STEM education, including curriculum adaptation and teacher training, while also examining its potential to improve personalised learning and teaching effectiveness.
2023	Govender, R. [17]	The findings demonstrate the potential of large language models such as ChatGPT to interactively engage students, provide personalised attention, and explain mathematical concepts. However, the study also highlights the need to monitor AI-assisted learning to mitigate overreliance that may hinder the development of logical reasoning.
2023	Nam, B. H., and Bai, Q. [40]	This study examines ChatGPT's effects on STEM research and higher education, including challenges related to research, teaching, and academic work. The authors emphasise ethical research, responsible publishing, and the continued importance of human intelligence, calling for proactive dialogue and policy development to support responsible AI adoption.
2023	Yilmaz, R., and Yilmaz, F. G. K. [61]	ChatGPT integration in programming classes can enhance computational thinking, programming self-efficacy, and motivation, while fostering creativity, algorithmic thinking, collaboration, and problem-solving skills. However, the effect on motivation may diminish during challenging tasks, indicating the need for supplementary pedagogical approaches.
2023	Chng, E., Tan, A. L., and Tan, S. C. [10]	The study explores emerging technologies in STEM education and identifies key research areas, including overcoming adoption barriers, understanding technology-enabled learning, and assessing pedagogical benefits. It emphasises teacher training and the importance of considering resources, purpose, outcomes, and pedagogy when integrating technology.

Year	Researcher	Findings
2023	Nagaraj, B. K., Kalaivani, A., Begum, S., Akila, S., and Sachdev, H. K. [39]	The research underlines that AI has significant potential to transform STEM higher education by enhancing personalised learning, student engagement, and assessment. However, its integration requires addressing ethical, privacy, and equity concerns through clear policies and guidelines. Professional development for educators, institutional collaboration with AI experts, and supportive policies are essential for effective and responsible implementation.
2022	Xu, W., and Ouyang, F. [58]	This research examines the gaps and difficulties involved in integrating AI into STEM education. It explores challenges related to adapting AI tools, teachers' knowledge and AI literacy, and the impact of AI on teaching practices, including individualisation, automated assessment, and simulation-based learning.
2022	Jang, J., Jeon, J., and Jung, S. K. [25]	A STEM-based AI education programme enhanced elementary students' creative problem-solving skills, attitudes towards AI, and AI literacy, as demonstrated by pre- and post-test results. Student feedback indicated positive reactions and increased acceptance of AI technologies as problem-solving tools.
2022	Akgun, S., and Greenhow, C. [1]	The application of artificial intelligence in K–12 education holds significant potential for personalising learning and enhancing educational outcomes; however, it also presents ethical challenges, including fairness, privacy, and accountability. The authors emphasise the necessity of policies, pedagogical guidelines, and educational practices that support the fair and responsible use of AI technologies in schools.
2021	Hwang, G. J., and Tu, Y. F. [22]	The authors demonstrate that artificial intelligence holds significant potential for enhancing mathematics education through personalisation and intelligent tutoring systems. However, they also highlight its limited application in certain areas of mathematics and across different educational levels and stress the need for further research and greater teacher involvement in AI tool development.
2020	Yannier, N., Hudson, S. E., and Koedinger, K. R. [60]	The paper explores how mixed reality and artificial intelligence can enhance active learning in STEM education. The Intelligent Science Station uses AI to monitor physical experiments and provide personalised, real-time feedback. The research indicates that combining directed hands-on instruction with constructive inquiry can improve understanding of scientific principles compared with a standalone inquiry approach.

Table 6 provides a summary of the analysed research articles, including key bibliographic details such as year of publication and author(s). In addition, the table categorizes each study according to its primary focus whether it addresses innovations, challenges, or trends, in the context of AI in STEM education. It also outlines the main research question(s) explored in each paper.

Table 6. Mapping of studies to research questions and disruption focus

Year	Researcher	Disruption	RQ1	RQ2	RQ3
2025	Opesemowo, O. A. G. [41]	Pedagogical	✓	✓	✓
2024	Ilić, J., Ivanović, M., & Klašnja-Milićević, A. [24]	Trends/Innovation	✓	✓	✓
2024	Joseph, O. B., & Uzondu, N. C. [26]	All	✓	✓	✓
2024	Egara, F. O., & Mosimege, M. [13]	Challenges/Innovation	✓		✓
2024	Llerena-Izquierdo, J., Mendez-Reyes, J., Ayala-Carabajo, R., & Andrade-Martinez, C. [34]	Challenges/Innovation	✓	✓	
2024	Wijaya, T. T., Yu, Q., Cao, Y., He, Y., & Leung, F. K. S. [57]	Challenges		✓	✓
2024	Silva, C. A. G. d., Ramos, F. N., de Moraes, R. V., & Santos, E. L. d. [48]	Challenges/Innovation	✓	✓	
2024	Ouyang, F., & Xu, W. [42]	All	✓	✓	✓
2024	Selvam, A. A. A. [46]	Challenges/Innovation	✓		✓
2024	Beege, M., Hug, C., & Nerb, J. [4]	Trends			✓
2024	Mirea, N., Palade, M., & Gaureanu, A. [35]	All	✓	✓	
2024	Li, T., Ji, Y., & Zhan, Z. [33]	Challenges/Innovation	✓		
2024	Saradha, P., Gomathi, R. D., Mythili, M., Jamuna, G., Karthick, S., Indhumathi, N., . . . , & Hariharan, G. [45]	Challenges/Innovation	✓	✓	✓
2023	Chiu, T. K. F., & Li, Y. [8]	Challenges		✓	✓
2023	Park, J., Teo, T. W., Teo, A., et al. [43]	Challenges/Innovation	✓	✓	✓
2023	Triplett, W. J. [52]	Challenges	✓		✓
2023	Wang, T., Lund, B. D., Marengo, A., Pagano, A., Mannuru, N. R., Teel, Z. A., & Pange, J. [56]	Trends/Innovation		✓	✓
2023	Triplett, W. J. [53]	All	✓	✓	✓

Year	Researcher	Disruption	RQ1	RQ2	RQ3
2023	Govender, R. [17]	All	✓	✓	✓
2023	Nam, B. H., & Bai, Q. [40]	Challenges	✓		✓
2023	Yilmaz, R., & Yilmaz, F. G. K. [61]	Challenges/Innovation		✓	✓
2023	Chng, E., Tan, A. L., & Tan, S. C. [10]	Trends/Innovation	✓	✓	✓
2023	Nagaraj, B. K., Kalaivani, A., Begum, S., Akila, S., & Sachdev, H. K. [39]	All	✓		✓
2022	Xu, W., & Ouyang, F. [58]	All	✓	✓	
2022	Jang, J., Jeon, J., & Jung, S. K. [25]	Trends/Innovation		✓	✓
2022	Akgun, S., & Greenhow, C. [1]	All	✓	✓	
2021	Hwang, G. J., & Tu, Y. F. [22]	All	✓	✓	
2020	Yannier, N., Hudson, S. E., & Koedinger, K. R. [60]	All	✓	✓	✓

4. Results and Key Findings

This systematic review analysed 29 peer-reviewed articles. A substantial proportion of the reviewed studies (n = 9) focused predominantly on the application of chatbot tools based on Large Language Models (LLMs) in STEM education [20]. This finding is consistent with a broader trend highlighted in recent literature, indicating that LLM-based AI chatbot tools have contributed to a paradigm shift in the development and application of artificial intelligence [44]. Moreover, LLMs have been identified as an important milestone in the recent development of AI [15] and have significantly influenced the ways in which artificial intelligence is understood and applied across different domains [29].

The remaining studies examined, in a relatively balanced manner, the application of various AI technologies and solutions. These included specific AI tools designed for STEM education, some of which were developed by the authors themselves (n = 3), as well as broader analyses of AI applications, including intelligent tutoring systems, educational robotics, computer vision algorithms, personalised learning systems, facial recognition technologies, and predictive analytics systems. To address the research questions, the findings are organised into three thematic categories reflecting the key innovations, emerging trends, and challenges associated with the integration of AI in STEM education:

1. The key pedagogical, ethical, and technical challenges associated with integrating AI into STEM education;
2. The transformation of STEM education through AI tools in comparison with traditional teaching methods;
3. The influence of teachers' ICT competencies and professional development on the successful integration of AI in STEM education, as well as the challenges they face in adopting AI-based instructional strategies.

RQ1: What are the key pedagogical, ethical, and technical challenges of integrating AI into STEM education?

Of the 29 studies included in this review, 79.31% (n = 23) explicitly addressed various challenges related to AI integration in STEM education. Among these, 73.91% (n = 17) discussed pedagogical challenges, particularly those associated with the instructional use of AI in classroom settings. Ethical concerns, especially those related to data privacy and algorithmic transparency, were addressed in 78.26% (n = 18) of the studies. Additionally, 65.22% (n = 15) identified technical issues, including infrastructure limitations, platform interoperability, and implementation complexity, as significant barriers (Figure 4).

A central issue reported across the literature is the reliability of AI-generated responses and feedback. Approximately 47.83% (n = 11) of the articles indicated that inaccurate or misleading AI-generated feedback may hinder students' independent learning, particularly when learners lack the critical skills required to assess the accuracy and validity of AI-generated content. This issue also creates difficulties for teachers attempting to monitor and support individualised learning pathways.

The integration of AI into education is recognised as a complex and multifaceted process involving strategic planning, pedagogical adaptation, continuous professional development, and institutional policy guidelines. These issues, however, are not independent. Several studies emphasised the interdependence of pedagogical, ethical, and technological challenges. For instance, the effective pedagogical application of AI tools depends not only on appropriate instructional design but also on robust data protection mechanisms and reliable technological infrastructure [10,28,48,53].

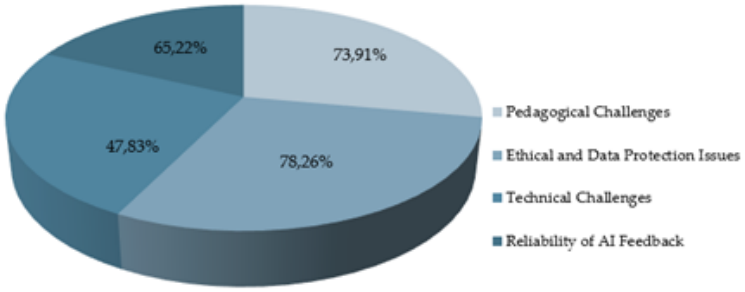


Fig. 4. Distribution of reported challenges in AI-integrated STEM education

Further analysis revealed that students' over-reliance on AI for problem-solving may hinder the development of critical thinking and foundational skills, thereby posing significant pedagogical challenges [39,40,41,57]. Several studies emphasised the need for teachers to adapt their instructional strategies in ways that align with AI capabilities while ensuring equitable access for all learners [32]. The ethical concerns highlighted across the literature include algorithmic bias, data privacy breaches, and the potential for AI to exacerbate existing educational inequalities [58,28,35].

In addition to infrastructural constraints, the technical challenges identified encompassed the lack of intuitive design, interoperability and compatibility limitations across different AI tools and learning management systems, and the need for continuous technical support. Effectively addressing these multifaceted challenges is essential to ensure the responsible and equitable use of AI within STEM education.

Future research should prioritise the development of practical guidelines and implementation frameworks that promote constructive and pedagogically sound AI integration in educational settings.

RQ2: How are modern AI tools reshaping STEM teaching and learning compared to traditional methods?

The integration of modern AI tools is increasingly transforming teaching and learning processes within STEM disciplines. Of the 29 reviewed studies, 72.41% (n = 21) focused on comparing AI-supported instructional methods with traditional teaching approaches. The most prevalent shifts include:

- Personalised learning facilitated by intelligent tutoring systems 52.38% (n = 11),
- Automated feedback mechanisms to support real-time guidance 42.86% (n = 9),
- Active learning through adaptive technologies and mixed-reality interfaces 76.19% (n = 16).

These innovations are reported to enhance student engagement, enable rapid identification of learning needs, and foster higher-order cognitive skills such as analysis, synthesis, and problem-solving. However, 28.57% (n = 6) of the studies also raised caution regarding the uncritical or unstructured use of AI, emphasising the importance of aligning these technologies with well-defined pedagogical goals and instructional design principles (Figure 5).

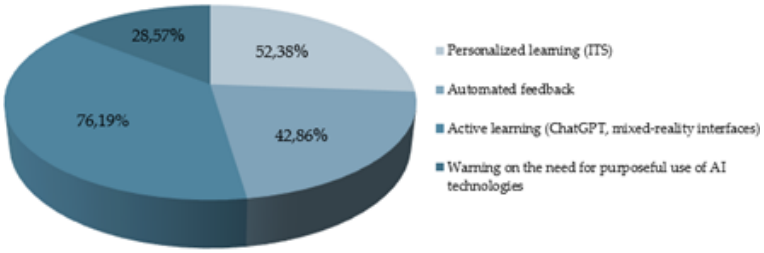


Fig. 5. Prevalent shifts enabled by AI

AI tools present a mixed impact on STEM education. On the one hand, they have been shown to improve learning quality and student engagement, as reported in 33.33% (n = 7) of the analysed studies. One contributing factor may be AI's ability to visualize abstract STEM concepts, which can enhance student motivation – highlighted in 42.86% (n = 9) of the papers.

However, students with limited prior knowledge in a particular STEM subject may experience minimal or even negative effects from AI-based learning. Specifically, 23.81% (n = 5) of the studies indicated that in such cases, academic performance remained stagnant or declined when AI tools were used (Figure 6).

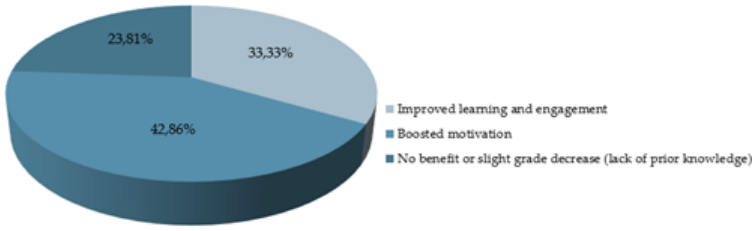


Fig. 6. Effects of AI tools in STEM education

Without a purposefully designed constructivist framework, students may develop an unhealthy dependence on AI tools, while educators risk implementing technology in uncritical ways. These findings underscore the importance of ensuring that AI serves as a supportive and pedagogically aligned tool, rather than a substitute for meaningful, intentional teaching.

RQ3: How can teachers' ICT skills and professional development influence the successful integration of AI in STEM education, and what are the challenges they face in adopting AI-based teaching methods?

Among the 29 analysed studies, 65.52% (n=19) identified teachers' ICT competencies and professional development as critical enablers of effective AI integration in STEM education. Furthermore, 24.14%, (n = 7) of the articles reported that insufficient digital skills and unfamiliarity with AI tools among educators represent significant barriers to implementation.

Deficiencies in teacher training and institutional support result in a lack of awareness and preparedness regarding the contextual adaptation of AI technologies to diverse educational environments. Several studies emphasised that the development of instructional units and the alignment of teachers' attitudes toward new AI-based approaches are facilitated by ongoing professional development, collaboration with instructional designers, and the provision of concrete, detailed, structured and algorithmic guidelines.

In addition to initial teacher training, there is a recognised need for continuous professional support. Five studies (17.24%) emphasised the importance of mentoring initiatives and the establishment of communities of practice that proactively offer structured opportunities for collaborative problem-solving and peer-learning. These forums are perceived as essential mechanisms for enhancing the quality, relevance, and sustainability of AI-based teaching strategies and for supporting teachers in navigating emerging instructional demands posed by artificial intelligence technologies (Figure 7).

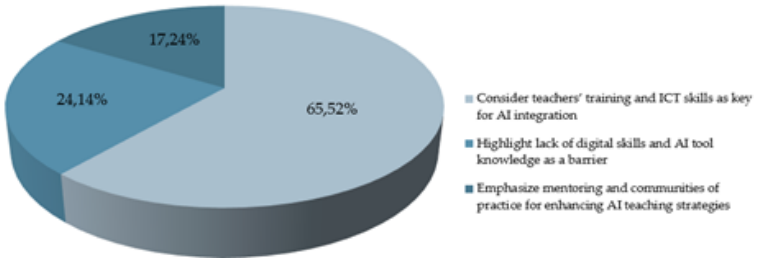


Fig. 7. Teachers' professional development and ICT competencies in the integration of AI in STEM education

Moreover, the reviewed literature emphasises the critical role and responsibilities of institutions in supporting AI integration. 37.93% (n = 11) of the analysed studies reported that schools and educational districts must provide targeted support, including the provision of AI-integrable technologies and hands-on technical assistance to ensure the successful adoption of AI in STEM education. Institutional support also involves the ability to facilitate pedagogically sound classroom integration, enabling educators to fully utilize AI tools within STEM learning environments. In the absence of such infrastructural backing, even highly competent teachers may struggle to meaningfully apply AI technologies to enhance the learning experience.

As earlier emphasised, the strategic and sustainable integration of AI in STEM education requires addressing persistent systemic challenges. These include comprehensive and ongoing teacher professional development, the creation of robust and collaborative professional learning communities, and a deep, institutional commitment to transformative pedagogical change.

AIEd presents both opportunities and challenges in improving instructional efficiency and learning outcomes. To harness these opportunities effectively, educators must possess strong ICT competencies and engage in continuous professional development. Teachers play a pivotal role in implementing AI-based curricula. Achieving the full potential of AI-enhanced STEM education, depends on both a clear pedagogical understanding and a sustained willingness among teachers to advance their digital literacy and adapt to evolving technologies.

STEM educators, often tasked with teaching complex disciplinary content, may find that AI tools offer valuable support in reducing instructional burden [54]. As a result of these intersecting demands, where technology and innovation converge with disciplinary knowledge, there has been a notable increase in literature reviews and bibliometric analyses focusing on the relationship between AI and STEM education [28,50,56], as well as specific domains such as science education [2], and mathematics education [22,11].

5. Discussion

This study aimed to provide a holistic evaluation of the integration of AI into STEM education based on a systematic review of 29 peer-reviewed articles published between 2020 and March 2025. The findings identify key gaps in the existing literature and uncover critical concerns associated with the use of AI in STEM education.

Based on the analysis, three overarching themes emerged: (i) the integration of AI into teaching frameworks, ethical considerations, and technological infrastructure; (ii) the pedagogical implications of AI tools compared with traditional teaching methods; and (iii) the role of teachers' ICT skills and ongoing professional development in enabling effective AI-enhanced instruction.

The results highlight the complexity of AI integration, particularly across ethical, pedagogical, and technical dimensions. In particular, 79.31% of the reviewed studies emphasised challenges related to data protection, algorithmic bias, and system robustness, concerns that align with previous research highlighting the potential for inappropriate AI implementation to exacerbate educational inequalities [34,53,57]. A recurring issue across 47.83% of the reviewed studies was the unreliability of AI-generated feedback, which may negatively affect student learning, particularly when learners lack the skills required to critically assess the accuracy of AI-generated content. This challenge may impair the development of learner autonomy and complicate teachers' efforts to tailor instruction. The strong interplay between pedagogical, ethical, and technical concerns underscores the need for a holistic integration strategy rather than isolated interventions.

Despite AI's potential to personalise instruction and support skill development, 34.48% of the articles questioned the effectiveness of modern AI applications in achieving meaningful educational outcomes. Concerns were raised about overdependence on AI, which may reduce active participation, problem-solving, motivation, and self-regulated learning [40,41,57]. AI systems may also function as "black boxes", providing surface-level assistance without necessarily engaging students in deeper cognitive processes.

The ethical implications extend beyond data protection to encompass the potential marginalisation of the teaching profession. If AI is positioned as a replacement for teachers rather than as a tool to enhance their capabilities, education risks losing essential human qualities such as empathy, adaptability, and nuanced instructional judgement. To preserve these aspects, teachers should be actively involved in designing and implementing AI-based educational solutions [47,37]. Future research should therefore prioritise models in which AI serves to augment rather than replace educators, particularly in STEM disciplines.

A significant portion of the literature (72.41%) explored comparisons between traditional and AI-based instructional approaches. Key shifts identified include personalised learning through intelligent tutoring systems (52.38%), automated feedback tools (42.86%), and the promotion of active learning through adaptive technologies and mixed-reality platforms (76.19%). While these innovations show promise, they do not benefit all learners equally. In 23.81% of the studies, students with limited prior STEM knowledge showed stagnation or decline in learning outcomes, reinforcing the importance of intentional instructional design and appropriate pedagogical frameworks. These findings highlight the importance of carefully designed learning environments that support the purposeful and effective use of AI technologies.

The role of teacher preparedness is central to successful AI integration. A total of 65.52% of the studies stressed the importance of ICT proficiency and ongoing training, while 24.14% reported low digital literacy and limited familiarity with AI tools as barriers. This digital divide limits educators' capacity to adapt AI technologies to context-specific teaching needs [43,52,59].

A disconnect between institutional support and teacher needs was also evident. Only 17.24% of the reviewed studies recognised the vital role of mentorship initiatives and professional learning communities in facilitating AI integration. These collaborative spaces are crucial for exchanging practical experiences, encouraging peer learning, and fostering collective problem-solving within real-world educational contexts. The limited attention given to these support mechanisms constitutes a critical deficiency in current implementation strategies and may undermine the long-term success of AI adoption in educational institutions [37,47].

Providing adequate infrastructure, AI-compatible systems, and ongoing technical support is identified as a core institutional responsibility in 37.93% of the reviewed studies. Even highly skilled educators require adequate organisational support to implement AI effectively. Successful integration therefore demands vertical alignment between institutional leadership, investment in digital competence development, and a shared culture that fosters experimentation and reflective practice. Educational institutions should cultivate an environment in which innovation is encouraged and collaborative approaches involving teachers, administrators, and the broader educational community are prioritised.

6. Conclusions

This systematic review synthesised recent research on the application of AI in STEM education, covering 29 peer-reviewed studies published between 2020 and March 2025. The analysis highlights both the transformative potential of AI and the significant challenges that hinder its effective implementation in educational practice.

AI tools offer promising capabilities in automated assessment, personalised learning pathways, and enhanced student engagement. However, these benefits are often tempered by ethical, pedagogical, and technical barriers. Commonly identified constraints include infrastructure limitations, data security concerns, information governance gaps, and questions surrounding the trustworthiness of AI systems. Students' over-reliance on AI and insufficient development of critical thinking skills further complicate the pedagogical landscape.

The ethical implications of AI integration, particularly in relation to algorithmic bias, data privacy, and inequitable access to technology, remain only partially addressed in the literature. Despite these obstacles, the findings underscore the transformative potential of AI tools in STEM education. Technologies such as augmented reality and adaptive intelligent tutoring systems can foster deeper and more active engagement with learning content. However, negative consequences have also been observed, particularly among students with limited prior knowledge, who may experience greater difficulties in effectively using these tools. The successful integration of AI technologies into pedagogical frameworks ultimately depends on teachers' readiness and responsibility to guide their implementation.

Important factors include teachers' commitment to lifelong learning and their practical competence in using AI-based technologies. To support educators in implementing AI strategically and responsibly, this review emphasises the need for systematic institutional support, particularly through communities of practice, mentorship initiatives, and targeted training programmes. In addition, the role of academic institutions is critical. In-

stitutional support, combined with adequate technological infrastructure, is essential for fully realising the benefits of AI in STEM education.

The review also acknowledges a key limitation associated with reliance on secondary data sources, which may introduce publication bias and limit the understanding of contextual nuances in implementing AI across diverse educational environments. Moreover, the predominant focus on short-term outcomes in the reviewed studies often overlooks the long-term implications and sustainability of AI integration.

To fully understand the impact of AI on STEM education, further empirical research is required, particularly involving participants from elementary, secondary, and higher education levels. Longitudinal studies are crucial for assessing the long-term effects of AI on educational systems. Moreover, when evaluating the equity and inclusiveness of AI applications, special attention should be given to students with limited digital literacy and prior knowledge, as they may be particularly vulnerable to disadvantage resulting from rapid technological changes.

A substantial number of the reviewed studies focused on the application of chatbots in STEM education. Given the period in which these studies were conducted and the rapid pace of development in this research area, the analysed chatbot tools did not incorporate Retrieval-Augmented Generation (RAG) approaches or explicit semantic representations of STEM domain knowledge. This can be regarded as a potential limitation of the reviewed literature. The integration of RAG and explicit semantic domain representations could enable more accurate, up-to-date, and domain-specific responses, thereby reducing the occurrence of hallucinations. Chatbot systems that combine LLMs with RAG mechanisms and a semantic knowledge layer may be particularly beneficial for students who lack sufficient prior knowledge in STEM domains. Accordingly, future research should examine emerging studies employing RAG for querying STEM domain-specific databases and systems incorporating semantic knowledge layers. Such systems are expected to become increasingly prevalent and may allow LLMs to function primarily as components for generating coherent and human-readable responses.

The sample size may be considered relatively small. One reason for this lies in the selection criteria applied during the PRISMA-based study identification and screening process. The number of studies increased substantially during the analysed period from 2020 to 2025. Given the rapid development of AI technologies, including the emergence of chatbot systems incorporating RAG and semantic modules and the increasing adoption of multimodal functionalities in STEM education, it is reasonable to expect that the volume of related research will continue to grow. Consequently, future studies are expected to include larger samples and incorporate research on more complex and technologically advanced AI-driven STEM education applications.

AI holds transformative potential for education by enabling personalised instruction, real-time feedback, and the development of essential cognitive skills. However, realising this potential requires a carefully balanced approach that prioritises ethical, equitable, and inclusive integration strategies.

Key challenges, such as algorithmic bias, transparency of AI systems, and data protection, must be addressed through robust regulatory and institutional frameworks. The evolving role of teachers also requires particular attention. With appropriate training, active involvement in AI implementation, and institutional support, teachers can mitigate concerns regarding job displacement and maximise the pedagogical value of AI. Socio-

cultural sensitivity and community engagement are equally important for ensuring trust and fairness in AI applications.

Future research should explore diverse models of professional development, identify best practices for pedagogical integration, and evaluate institutional strategies that support ethical and sustainable AI adoption. In addition, future studies should expand literature searches to include a broader range of academic databases and repositories, such as Scopus, Web of Science, IEEE Xplore, ERIC, ACM Digital Library, SpringerLink, and ScienceDirect, to ensure more comprehensive coverage and reduce potential source bias in research on AI integration in STEM education.

In conclusion, unlocking the potential of AI in STEM education requires interdisciplinary collaboration, continuous evaluation, and a shared commitment to ethical, inclusive, and pedagogically sound implementation. Only through the synergistic efforts of educators, policymakers, technologists, and learners can AI be responsibly leveraged to advance 21st-century education.

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