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(Review Article)

The transformation of STEM education through educational chatbots and digital technologies

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Abstract

The rapid evolution of digital technologies has profoundly altered education, with STEM (Science, Technology, Engineering, and Mathematics) disciplines experiencing some of the most far-reaching changes. Through digital innovations, educational settings have become increasingly student-centered, and students' access to cutting-edge technological tools has deepened their comprehension of difficult topics. Meanwhile, among all digital technologies, educational chatbots have been recognized as highly interactive systems through which students can engage in continuous interaction with instructional support systems and receive feedback tailored to their individual needs. This article examines the evolving landscape of STEM education through the lens of educational chatbots and digital technologies. First, it comprehensively analyzes the ways in which digital support in learning not only redefines the role of teachers but also creates new pathways for students' motivation and individual growth. Secondly, it highlights educational chatbots as accessible digital companions that aid students both in the classroom and at home. The paper is organized around a systematic review of the literature addressing two core themes: digital transformation in education and chatbot-supported learning environments. Results indicate that educational chatbots serve as valuable tools in STEM learning by providing targeted, immediate assistance and consistent access to online content at any time. Moreover, chatbot-based learning environments are seen as drivers of student engagement and instruments for educational inclusiveness.Educational chatbots are powerful building blocks of digitally transformed STEM education, and their role in education is expected to expand considerably in the years ahead. When combined with teaching methods, they can enable a more dynamic, hands-on, learner-driven way of acquiring STEM skills.

Keywords: STEM education; Educational chatbots; Digital transformation; Artificial intelligence in education; Digital learning; Technology-enhanced learning.

1. Introduction

Over the past few decades, the roles of science, technology, engineering, and mathematics (STEM) in education have been significantly redefined due to the emergence of various digital technologies (Hillmayr et al., 2020; Cao et al., 2025). The invention of new digital technologies has altered the way teachers conduct lessons and opened up new avenues for students to acquire knowledge independently (Almalki, 2020; Chen et al., 2020; Chassignol et al., 2018). As such, digital tools have converted traditional teaching methods into interactive learning experiences through which students learn scientific and mathematical concepts directly (Redecker, 2017; Selwyn, 2016).

The role of digital technologies in supporting learner development is gaining further traction within the context of the educational reforms that have been initiated in many countries (Redecker, 2017; Sophos, 2025). One of the key goals of

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education is to develop students' digital competence, which requires STEM in teaching and learning (Bybee, 2013; Honey et al., 2014). For this reason, digital technology in STEM is at the forefront of educational planning aimed at preparing a workforce capable of navigating technological innovations (Simos, 2025a; Simos, 2025b; Simos, 2025c).

Technology-rich learning environments offer possibilities for better learner-directed and personalized learning experiences (Dede, 2014; Spector, 2014). Through the use of virtual reality and augmented reality, multimedia presentations and interactive whiteboards, students are able to collaborate through technology while teachers facilitate and guide inquiry-driven learning (Means et al., 2014; Mayer, 2014; Azevedo & Aleven, 2013; Bruner, 1966; Zimmerman, 2002). Such environments provide opportunities for immediate student feedback and interactive group work and foster deeper understanding through project-based learning and hands-on activities (Marques et al., 2020). Technology-enhanced learning environments have become recognized as ideal places of collaborative knowledge creation, development of higher order thinking skills, and increasing students' control over their learning (Wang et al., 2015). Thus, the evolution of digital technologies, particularly advanced artificial intelligence systems, adaptive learning platforms, and intelligent tutoring systems, is being leveraged to increase the efficacy and efficiency of student learning process (Holmes et al., 2022; Zawacki-Richter et al., 2019).

Educational chatbots are one of the newer digital technologies that are gaining a lot of attention as effective tools for supporting student learning through a conversational approach (Fryer & Carpenter, 2006; Fryer et al., 2017; Moorhouse & Kohnke, 2020). Educational chatbots allow students to interact with tutors and query them anytime by giving instant responses to students' problems using natural language communication (Pergantis & Drigas, 2024; Pergantis et al., 2025; Moraiti et al., 2022, Drigas A et al. 2016). Besides the physical classroom, the use of educational chatbots supports a continuing supply of learning (Winkler & Söllner, 2018; Okonkwo & Ade-Ibijola, 2021). They also present a valuable support system for students in their STEM learning journey by not only giving instant feedback but also offering tailored tutor support (Alemdag, 2023; Huang et al., 2025). When it comes to understanding STEM subjects, particularly in the areas of concept acquisition and the development of problem-solving skills, students face multiple obstacles (Margot & Kettler, 2019). Therefore, providing learners with personalised explanation and guidance through a chatbot may help them overcome learning difficulties and sustain their progress (Luckin et al., 2016). Consequently, chatbots, functioning as educational agents, are being integrated into various disciplines and educational institutions as a major aspect of digital transformation in education (Zhai et al., 2021; Luan et al., 2020). The use of digital support in the educational environment offers learners the opportunity to study without the constraints of time and place (Bates, 2019; Veletsianos& Houlden, 2019). In addition, this degree of flexibility creates an environment that is conducive to inclusiveness and further helps students with diverse learning needs (UNESCO, 2021).

Nonetheless, while digital technologies offer great opportunities, they also pose challenges for educational institutions and instructors alike (Luan et al., 2020; Sophos, 2025). To effectively utilize digital tools, teachers must first be given proper training (Ertmer & Ottenbreit-Leftwich, 2010; Tondeur et al., 2017). Besides this, there are also concerns related to the dependability and ethical use of artificial intelligence technologies in education (Williamson & Eynon, 2020). Therefore, the main aim of this paper is to explore how STEM education has been transformed through the integration of digital technologies and educational chatbots in modern learning environments (Smutny & Schreiberova, 2020; Gusenbauer & Haddaway, 2020). It is not just a theoretical discussion but a comprehensive study of digitally supported learning environments and how they contribute to the reshaping of teaching methodologies as well as student support and learning facilitation.

1.1. Research Questions

The present study examines the transformation of STEM education through the integration of digital technologies and educational chatbots. The study addresses the following research questions:

- RQ1: How does digital transformation reshape STEM learning environments and instructional practices?
- RQ2: How are educational chatbots integrated into modern digital STEM classrooms?
- RQ3: What opportunities and challenges emerge from the use of educational chatbots in digitally transformed STEM education?

2. Methodology

This research relies on a structured literature review to study how STEM education is being changed by the inclusion of digital technologies and educational chatbots (Gusenbauer & Haddaway, 2020). A literature review approach was adopted in order to synthesize the latest developments in STEM education supported by digital tools and to identify the major trends shaping today's educational settings (Snyder, 2019; Zawacki-Richter et al., 2019). The literature search was directed towards discussing digital transformation in education, technology-enhanced learning environments, and conversational technologies for education (Winkler & Söllner, 2018; Okonkwo & Ade-Ibijola, 2021). In particular, studies addressing digital technology integration in STEM education and chatbot-supported learning environments in contemporary educational contexts were examined (Holmes et al., 2022; Luan et al., 2020). Relevant articles were identified through systematic searches of major academic databases, including Scopus, Web of Science, ERIC and Google Scholar. The search was conducted for studies that were published in the range from 2010 to 2025 to include the latest advancements in digital learning environments and AI technologies in education.

Seventy scientific papers illustrating digital learning environments, AI applications, and educational chatbots in STEM education composed the final dataset. These studies were analyzed qualitatively to identify the prevailing themes in the digital transformation of STEM education and the emerging role of chatbot-supported learning environments (Braun & Clarke, 2006). The analysis was conducted at three main levels: the development of digital learning environments, the incorporation of educational chatbots into current STEM classrooms, and the future directions of chatbot-enabled STEM education. This methodological framework provides a structured basis for exploring how digital technologies are reshaping STEM education and how chatbot-supported environments contribute to the formation of new educational ecosystems.

3. Digital Transformation in STEM Education

3.1. Digital Transformation Models in STEM Education

Digital transformation refers to the integration of ICT tools into educational systems, reshaping pedagogical, organizational, and technological practices (Selwyn, 2016; Hillmayr et al., 2020), and it is widely considered one of the most significant changes in the field of education today (Bamicha & Drigas, 2022; Galitskaya & Drigas, 2020; Chaidi et al., 2021). Accordingly, driven by the broader digital transformation movement in education, digital technologies have been introduced into STEM education at the pedagogical, didactical, and organizational levels (Redecker, 2017; Bates, 2019).

Nowadays STEM education deeply depends on digital learning ecosystems where pupils use different technological tools to study (Hattie & Timperley, 2007; Shute, 2008; VanLehn, 2011). Such learning ecosystems can be based on the use of learning management systems, online platforms, interactive simulations, and artificial intelligence-supported learning tools (Holmes et al., 2022; Zhai et al., 2021). Besides that, the integration of these technologies fosters flexible learning environments that extend well beyond the physical classroom (Selwyn, 2016; Veletsianos & Houlden, 2019). In this regard, a central function of digital transformation in STEM education is that it allows the class to move on from teacher-driven instruction to a digitally led learning environment where instructional methods foreground the student’s active role and autonomous learning (Zimmerman, 2002; Bruner, 1966). Digital transformation models simultaneously give students the opportunity to work independently through interactive digital resources and encourage exploratory engagement with new knowledge (UNESCO, 2021). Such models not only implement active learning but also deepen students' comprehension of scientific and mathematical concepts (Dede, 2014; Spector, 2014).

Also, a major feature of digital transformation in STEM education is the creation of smart learning environments (Tuomi, 2018). Smart learning environments utilize digital technologies, AI systems, and interactive platforms together to offer adaptive and personalized learning opportunities. Such environments provide for uninterrupted learning and give students the freedom to use educational materials whenever required (Holmes et al., 2022; Tuomi, 2018). Furthermore, digital transformation has given rise to hybrid learning models which connect the traditional classroom with the online learning environment (Henderson et al., 2017; Kelley & Knowles, 2016). Hybrid learning environments enable learners to have more freedom in their learning and support STEM learners to be self-directed, i.e., they provide additional time for practice and revision (Means et al., 2014; Bond et al., 2020). The rising utilization of artificial intelligence technologies is another defining feature of digitally transformed STEM education. AI technologies are capable of processing learning data and offering personalized learning paths that align with each student's needs. Such technologies render the learning process more efficient and have a positive effect on learning results (Zhai et al., 2021; Roll & Wylie, 2016). The integration of such technologies also promotes inclusivity by enabling STEM students to access educational resources in ways that suit their individual circumstances (Fitas, 2025; Navas-Bonilla et al., 2025). Digitally supported learning environments provide, among other things, instructional materials and individualized support, to students with diverse learning needs, making STEM education more equitable (UNESCO, 2021).

Nevertheless, despite all the advantages of digital transformation, educational institutions are still facing several significant challenges, particularly in developing strategies for digital technology integration into pedagogical practices (Margot & Kettler, 2019). Besides, in order to use digitally supported learning activities teachers should be motivated and trained (Tan et al., 2025). The key to achieving successful digital transformation is the combination of technological innovation and pedagogical goals (Tondeur et al., 2017). In short, digital transformation is a multi-faceted process which at a minimum entails technological innovation, pedagogical change, and institutional development (Redecker, 2017; Bates, 2019). As part of digitally transformed STEM education, educational chatbots are significant because they provide learners with the opportunity for continuous interaction and to tailor the learning to their preferences (Winkler & Söllner, 2018; Okonkwo & Ade-Ibijola, 2021).

3.2. Hybrid and Digital STEM Classrooms

The digital transformation of education has given rise to hybrid and digital-supported STEM classrooms that integrate traditional face-to-face teaching with online learning platforms (Henderson et al., 2017). Hybrid learning environments blend teaching in the physical class with digital platforms and online resources, thereby providing flexible learning arrangements through which students can continue to learn even after the end of the class (Means et al., 2014; Bond et al., 2020). These environments represent a marked departure from traditional models of instruction and offer STEM learning support in novel ways (Simos & Karabatzaki, 2025; Simos & Katsiampoura, 2025; Simos & Skordoulis, 2025).

Hybrid STEM classrooms give access to digital platforms for instructional materials and learning activities that complement the in-class teaching (Means et al., 2014). Learning management systems and online platforms offer a structured access to educational content by enabling students to study anytime and at their own pace by reviewing lessons, doing assignments, and engaging in learning activities (Bates, 2019). Thus, the use of digital platforms in the classroom enhances the flexibility of learning and helps to develop learner autonomy (Zimmerman, 2002). These digitally enhanced STEM classrooms are gradually being defined by the incorporation of interactive technologies that not only make student participation and engagement easier but also richer in quality (Hillmayr et al., 2020). For example, interactive simulations, digital laboratories, and multimedia environments allow students to both visually and practically explore scientific concepts and mathematical relationships (National Research Council, 2012; Xie et al., 2019). Additionally, such technologies not only support inquiry-based learning but also motivate students to actively construct knowledge through exploration and experimentation (Dede, 2014; Spector, 2014).

Availability of learning support is another hallmark of digitally transformed STEM classrooms (Bates, 2019; Veletsianos & Houlden, 2019). Students can take advantage of digital platforms to gain access to instructional materials and learning tools anytime (Selwyn, 2016). Not only do such platforms promote independent learning but also enable students to revisit challenging concepts when required. Constant access to learning resources is extremely helpful in STEM education where solid grasp of concepts is built by regular practice and review (Mayer, 2014). Adding to this, hybrid learning environments also maintain the collaborative nature of learning in STEM disciplines (Dillenbourg, 1999; Voogt et al., 2015). Online communication tools facilitate collaboration on projects and idea sharing among students both inside and outside class. Discussions and exchanges of knowledge are effectively promoted by collaborative digital environments (Dillenbourg, 1999; Siemens, 2013; Voogt et al., 2015). Through group work and shared inquiry problem-solving skills are developed (Johnson & Johnson, 2009). STEM classrooms that are digitally enhanced already contain elements of the smart classroom concept (Holmes et al., 2022; Tuomi, 2018). By smart classrooms, we understand those that utilize digital devices, online platforms, and artificial intelligence tools which enable them to provide interactive learning environments dynamically responsive to students' needs (Zhai et al., 2021). Besides providing students with adaptive learning experiences, these learning environments also equip teachers with tools to monitor the progress and performance of their students (Holmes et al., 2022; Tuomi, 2018).

Educational chatbots are rapidly becoming an important part of hybrid STEM classrooms (Smutny & Schreiberova, 2020; Alemdag, 2023). Chatbots can be embedded into digital platforms and learning management systems and thus provide students with continuous assistance (Fryer et al., 2017; Moorhouse & Kohnke, 2020). Through conversational interaction, chatbots enable students to ask questions and get further explanations when working on assignments or studying independently. This form of assistance serves as a supplement to in-class teaching and enables students to get help outside of class hours (Winkler & Söllner, 2018; Okonkwo & Ade-Ibijola, 2021).

Hybrid learning environments supported by educational chatbots give students an opportunity to get help whenever they have difficulty (Luckin et al., 2016). Being able to get help at any time, students find it easy to study without interruptions and to cover a lot of ground by themselves (Bates, 2019; Veletsianos & Houlden, 2019). Therefore, chatbot-supported environments become part of a flexible and responsive learning system which is tailored to students' individual needs (Holmes et al., 2019). They also enable the provision of inclusive learning by offering different ways of accessing information and learning activities (UNESCO, 2021; Drigas & Sideraki, 2024). The flexibility of these learning environments which lets students work at their own pace and seek instructional support is also supportive to students with different learning needs. Thus, digital environments help make participation in STEM learning more equal (UNESCO, 2021).

However, alongside their benefits, hybrid STEM classrooms also pose significant challenges (Tondeur et al., 2017; Ertmer & Ottenbreit-Leftwich, 2010). For instance, teachers need to come up with new pedagogical methods for effectively incorporating digital tools into their teaching practices. In addition, well-coordinated and systematic planning of face-to-face and digital learning activities is a prerequisite to the success of hybrid learning environments (Kelley & Knowles, 2016). Poorly designed instructional strategies can prevent digital technologies from reaching their full educational potential (Tondeur et al., 2017). Hence, hybrid and digitally supported STEM classrooms can be said to be at the heart of the digital transformation of education (Henderson et al., 2017; Bond et al., 2020). Digital platforms, interactive technologies, and conversational learning tools jointly create learning environments that are sufficiently flexible and adaptive so as to provide learners with chances for continuous learning and engagement (Means et al., 2014; Selwyn, 2016). Educational chatbots can be considered as one of the most intriguing tools within these digital ecosystems since they deliver interactive assistance that is complementary to teacher-led instruction (Winkler & Söllner, 2018; Holmes et al., 2022).

4. Educational Chatbots in Modern STEM Education

4.1. Chatbots as Digital Learning Assistants

One of the rising trends in digitally augmented educational settings is the use of educational chatbots. Within the context of current STEM education, chatbots are seen as digital learning assistants that constantly aid learners with their educational tasks (Smutny & Schreiberova, 2020; Alemdag, 2023). Traditional digital learning resources do not offer the same level of interactive communication through natural language that chatbots do, which enables learners to receive detailed guidance and explanations in an adaptable and accessible manner (Winkler & Söllner, 2018; Okonkwo & Ade-Ibijola, 2021;Graesser et al., 2005; Nye, 2015; Wood et al., 1976).

Digital learning assistants prove valuable across multiple dimensions of a student's work. They answer students' queries immediately and also lead them by giving step-by-step instructions in a learning situation (Kirkwood & Price, 2014; Hsu et al., 2017; Kukulska-Hulme, 2012). The availability of continuous support can enhance students' independence while reducing the necessity for direct teacher intervention (Winkler & Söllner, 2018). This mode of support is highly desirable in STEM education given that students frequently encounter challenges when engaged in complex tasks or problem-solving activities (Luckin et al., 2016; Holmes et al., 2022). Thus, chatbots employed as digital learning assistants can serve as reliable companions that support learners throughout the various phases of their educational journey (Bickmore & Picard, 2005; Kose & Arslan, 2015; VanLehn, 2011). Learners may turn to chatbots not only for initial instructions but also for revisiting content and addressing areas of difficulty through further explanations (Okonkwo & Ade-Ibijola, 2021). This kind of support complements traditional face-to-face teaching and provides opportunities for learners to study even when they are not in school (Means et al., 2014).A practical advantage of chatbot-based learning assistance is their compatibility with a range of devices (Kukulska-Hulme, 2012). Besides computers, tablets and mobile phones are other means through which chatbots can be accessed. Hence, students can receive educational support no matter where they are physically present. Such flexibility fosters uninterrupted learning and the students can learn in accordance with their own time and pace (Bates, 2019).

Educational chatbots further improve learning environments by minimizing the waiting time for support, which is one of the weaknesses of conventional classroom settings (Holmes et al., 2019). In traditional settings, students often have to wait for assistance from teachers or peers. By providing learners with instant answers, chatbots enable them to continue working without unnecessary delays. Uninterrupted interaction not only makes learning easier but also ensures that students stay concentrated on their educational tasks (Holmes et al., 2019).Beyond cognitive support, chatbots as digital learning assistants can also contribute to the organization of students' work (Luan et al., 2020). Reminders, directions, and information about assignments or other learning activities can be delivered to students by chatbots. Such organizational support not only helps students in effective learning management but also leads to better learning organization in digitally-enhanced environments (Luan et al., 2020).

Moreover, chatbots as digital learning assistants can facilitate communication between the students and the educational platforms (Winkler & Söllner, 2018; Okonkwo & Ade-Ibijola, 2021). Students can get assistance through chatbots in navigating digital learning environments and selecting learning materials that are most suitable for them (Dale, 2016; Baker & Inventado, 2014). The provision of such service is especially crucial in complicated digital settings where students must be assisted in accessing the resources they require (Veletsianos& Houlden, 2019).

Considering their range of functions and benefits, educational chatbots represent multifaceted and flexible digital learning assistants capable of supporting students within computer-based educational environments (Winkler & Söllner, 2018; Okonkwo & Ade-Ibijola, 2021). Their constant availability, ability to provide immediate feedback, and provision of guidance make these chatbots an extension of teaching resources in STEM classrooms (Holmes et al., 2022; Luckin et al., 2016).

4.2. Chatbots in Digital STEM Ecosystems

The digital transformation of STEM education has facilitated the construction of complex digital learning ecosystems where various technological tools cooperate for the sake of students' learning (Zhai et al., 2021; Holmes et al., 2022). Digital STEM ecosystems are composed of learning management systems, online educational platforms, digital resources, and AI-enhanced learning tools that not only coexist but are the integrated components of modern-day educational environments (Redecker, 2017; Selwyn, 2016).

Within these digital ecosystems, educational chatbots function as key communication channels through which students transmit their queries and receive relevant educational resources (Winkler & Söllner, 2018). Hence, through chatbots, learners interact with digital platforms in real time via conversational communication, which serves as the primary channel through which they receive support with minimal effort in accessing materials (Okonkwo & Ade-Ibijola, 2021). Conversational interaction reduces the cognitive demands associated with navigating digital systems, thereby allowing students to focus on learning activities rather than being distracted by technical procedures (Dale, 2016; Baker & Inventado, 2014; Heffernan & Heffernan, 2014; Kulik & Fletcher, 2016). It thus seems that embedding educational chatbots within learning management systems and online educational platforms is an effective way to offer continuous instructional support (Holmes et al., 2019). Being linked with digital platforms, these chatbots have the potential to guide student learning, providing direction and support so that students can study and complete assignments with greater confidence (Bates, 2019).

Chatbots are also well suited to support data-driven learning environments in which digital systems monitor students' learning activities in order to enhance instructional delivery (Baker & Inventado, 2014; Heffernan & Heffernan, 2014). AI-supported learning ecosystems make use of learning data in order to pinpoint students' needs and provide them with the most relevant forms of assistance (Roll & Wylie, 2016). As communication devices, chatbots can play the role of delivering personalized support that is based on the information gleaned from learning data (Zhai et al., 2021; Roll & Wylie, 2016). Such ecosystems make it possible for students to fluidly transition between face-to-face classroom instruction and independent study (Means et al., 2014; Bond et al., 2020). The initial point of contact for the students can be the classroom and then with the support of chatbots they can continue their studies via digital platforms (Bates, 2019). Such a transition and continuity become a means for the students to sustain their progress and achieve deeper learning over time (Means et al., 2014). Educational chatbots also facilitate the support of scalable learning environments in which the individualization aspect of support is maintained even when the student enrollment numbers are large (Zawacki-Richter et al., 2019).

Digital ecosystems that are supported by chatbots empower educational institutions to efficiently cater to students' academic needs without adding to teachers' workload (Holmes et al., 2022). Scalability is particularly significant in large educational systems and online learning environments (Holmes et al., 2022). These ecosystems are also advantageous from the point of view of accessibility (Fitas, 2025; Navas-Bonilla et al., 2025). Through conversational interfaces, students with varying levels of digital proficiency can interact with learning platforms more readily (Dale, 2016). The use of natural language communication lowers technical barriers and thereby fosters broader and more inclusive participation among learners in digitally-facilitated STEM education (UNESCO, 2021).

Even though it is true that they bring benefits, deploying chatbots in digital STEM ecosystems is not without its obstacles. Educational institutions have to ensure that chatbot systems not only align with the set of learning objectives but also that the educational content delivered by chatbots is reliable and accurate (Porayska-Pomsta et al., 2023). The role of teachers remains visible in the oversight of student interactions within chatbot-supported learning environments and in guiding students' use of digital tools (Williamson & Eynon, 2020).

Hence, educational chatbots are seen as one of the most important elements of digital STEM ecosystems nowadays (Zhai et al., 2021; Luan et al., 2020). Their inclusion in digital learning settings results in more flexible and interactive educational systems that are in line with the unfolding digital transformation of STEM education.

5. Opportunities and Challenges of Digital STEM Transformation

5.1. Opportunities of Digitally Transformed STEM Education

Digital transformation of STEM education offers a considerable number of opportunities for enhancing teachers' and learners' practices (Hillmayr et al., 2020; Sofroniou et al., 2025). It includes creating adaptable learning environments using digital tools that can accommodate students' individual needs and preferences (Tomlinson, 2014; Pane et al., 2017). Besides, students involved in digitally transformed schooling setups gain continuous access to teaching and learning resources which in turn leads to constant learning and learner independence (Means et al., 2014; Bates, 2019; Simos & Katsinis, 2026; Simos, Larios, &Papousti, 2026).Accessibility to learning resources is undoubtedly one of the key areas where digitally transformed STEM education presents significant opportunities (Selwyn, 2016; Veletsianos & Houlden, 2019). The shift to digital platforms makes available to students a wide range of instructional materials, including videos, simulations, interactive exercises, and online textbooks. Students are thus able to independently review content delivered in class and reinforce their skills outside of classroom hours (Mayer, 2014).

Digitally-`transformed STEM education also presents a valuable opportunity for establishing personalized learning environments where students have the liberty to learn at a pace which is most comfortable for them (Means et al., 2014; Bates, 2019; Tomlinson, 2014; Kelley & Knowles, 2016; Drigas et al., 2022; Mitsea et al., 2022&2023, Politi-Georgousi et al.2020). Students are afforded the opportunity to engage with challenging materials at their own pace and without external pressure, while also receiving additional support and explanations when their understanding falls short (Holmes et al., 2019; Luckin et al., 2016). Individualized and customized learning environments are not only geared towards making the learning processes more effective and efficient but are also capable of minimizing disparities in students' learning outcomes (Pane et al., 2017).Developing interactive learning experiences is one of the key opportunities that digitally transformed education offers (Hillmayr et al., 2020; Cao et al., 2025). Digital technologies enable students to observe and engage with scientific phenomena and mathematical concepts through simulations and interactive learning environments (National Research Council, 2012; O'Neil et al., 2005; Xie et al., 2019). Interacting with learning materials contributes to not only a deeper comprehensive understanding of the issues under study but also encourages active participation in the learning process (Dede, 2014; Spector, 2014).Educational chatbots play a central role in realizing these opportunities by providing continuous and personalized learning support. Chatbots afford students the opportunity to obtain explanations and guidance at any time when they encounter difficulties (Alemdag, 2023; Huang et al., 2025). Such continued access to educational support fosters greater learner independence and contributes to more efficient learning processes (Winkler & Söllner, 2018; Holmes et al., 2022).

A further opportunity afforded by digitally transformed STEM education is its support for collaborative learning environments (Dillenbourg, 1999; Siemens, 2013). With the aid of digital communication tools, students can work together on different projects and share ideas irrespective of their physical locations (Voogt et al., 2015). Collaborative learning environments facilitate knowledge exchange and at the same time, problem-solving skills are fostered through group work and discussions (Johnson & Johnson, 2009).Equally important is the capacity of digitally transformed STEM education to foster inclusive learning environments where learners can receive individual support, irrespective of their diverse learning needs. Such flexible learning environments help ensure equitable participation while simultaneously minimizing barriers to STEM learning (UNESCO, 2021; Drigas&Sideraki, 2024). In this same light, digital transformation has enabled educational institutions to develop learning systems that are highly scalable and capable of serving large numbers of students (Zawacki-Richter et al., 2019). Digital support allows the provision of learning support without the need for a proportional increase in instructional resources. This capacity is particularly advantageous in large educational systems and online learning environments (Holmes et al., 2019).To sum up, the digital transformation of STEM education holds considerable potential for creating flexible, interactive, and inclusive learning environments. Educational chatbots are a crucial component of such environments as they facilitate continuous interaction and individualized learning support.

5.2. Challenges of Digitally Transformed STEM Education

Alongside the considerable opportunities brought about by digital transformation, several challenges continue to hamper the effective implementation of digitally supported STEM education (Luan et al., 2020). Chief among these is probably the challenge of integrating digital technologies with existing educational practices (Margot & Kettler, 2019). This demands sufficient planning, not only to avoid conflict but to ensure alignment between technological tools and pedagogical objectives (Tondeur et al., 2017).

Teachers are at the forefront of implementing digitally transformed learning environments (Tan et al., 2025). For the smooth and effective integration of digital technologies, teachers need to acquire new skills and instructional methods

(Tondeur et al., 2017). However, many teachers still require additional training to use digital tools proficiently and to integrate them into classroom instruction (Margot & Kettler, 2019). If teachers are not adequately prepared, digital technologies will hardly realize their full educational potential (Ertmer & Ottenbreit-Leftwich, 2010).

Another challenge that warrants attention concerns the reliability of artificial intelligence-supported learning tools (Holmes et al., 2021; Porayska-Pomsta et al., 2023). For example, educational chatbots and AI systems sometimes may give inaccurate or incomplete feedback. Students may uncritically rely on information provided by chatbots without verifying its accuracy (Ganguly et al., 2026). Therefore, the role of the teacher in a chatbot-supported learning environment is highly crucial and cannot be replaced (Williamson & Eynon, 2020).Equally pressing are the ethical issues associated with the use of artificial intelligence in education (Williamson & Eynon, 2020; Porayska-Pomsta et al., 2023). Concerns about data privacy, algorithmic bias, and ethical use of technology have become central concerns in digitally supported learning environments (Holmes et al., 2021). Educational institutions have a responsibility to ensure that digital technologies are used in ways that respect students' rights and promote their ethical learning practices (Holmes et al., 2021).

Another obstacle to digital transformation is disparity in students' access to digital technologies. Not all students have access to digital devices and steady internet connections (Sophos, 2025). The gap in access to technology may lead to the emergence of new forms of educational inequalities and hence prevent some groups of learners from experiencing the benefits of digital transformation (Selwyn, 2016).Another consideration is long-lasting provision of resources for a digitally transformed educational system (Selwyn, 2016). Educational institutions must be conversant with aspects such as the problem of resource allocation for digital infrastructures and updating technological tools (Bates, 2019). Forward planning and continuous evaluation of digital learning initiatives are essential for long-term sustainability (Veletsianos& Houlden, 2019).

Besides this, consideration must be given to the cognitive demands that digitally transformed learning environments place upon students' cognitive capabilities made by digitally transformed learning environments (Mayer, 2014). Instances where digital tools may impede rather than support learning activities must be identified carefully and students' capacity to be overwhelmed by use of multiple digital tools simultaneously should be kept in mind while designing the instruction (Mayer, 2014).

Although digitally transformed STEM education presents challenges to which educators and students must adapt, it continues to evolve rapidly (Zhai et al., 2021; Zawacki-Richter et al., 2019). In order to realize the full potential of digitally transformed STEM learning environments, it will be necessary to integrate digital technologies and educational chatbots with pedagogical practices and at the same time address the outlined challenges (Tondeur et al., 2017; Holmes et al., 2021).

6. Discussion

The present study explored the transformation of STEM education through the integration of digital technologies and educational chatbots. Results of the literature review suggest that digital transformation has profoundly changed the very nature of present-day STEM education by offering students a more flexible learning environment and instructional approaches that are highly interactive (Smutny & Schreiberova, 2020; Popenici & Kerr, 2017; Gusenbauer & Haddaway, 2020). Digitally supported STEM education not only transcends the boundaries of the traditional classroom but also enables students to access instructional resources and learning support through a variety of flexible channels (Means et al., 2014; Bates, 2019).

These findings are consistent with previous research highlighting the growing role of artificial intelligence in education. Studies by Holmes et al. (2022) and Zawacki-Richter et al. (2019) emphasize that AI-supported systems, including educational chatbots, can enhance learner engagement and provide personalized support. Similarly, research by Winkler and Söllner (2018) demonstrates that conversational agents can act as complementary instructional tools in digitally enriched classrooms.The study review offers strong indications that hybrid learning environments are a fundamental aspect of digitally transformed STEM education (Henderson et al., 2017; Kelley & Knowles, 2016; Popenici& Kerr, 2017). Hybridclassroomsintegrateface-to-face instruction with digitally supported learning activities and enable students to carry on learning beyond the confines of scheduled class times. Such environments empower students to take control of their learning and continuously engage with STEM subjects (Bond et al., 2020).

Educational chatbots also seem to be a key feature of digitally transformed learning environments (Smutny & Schreiberova, 2020; Alemdag, 2023). As digital learning assistants, chatbots conduct conversational interaction with students and provide them with instructional guidance round-the-clock (Okonkwo & Ade-Ibijola, 2021; Fryer et al., 2017). Deploying them on digital platforms supports students' independent work by maintaining a high level of assistance and contributing to the creation of more responsive learning environments (Winkler & Söllner, 2018; Holmes et al., 2022).The development of digital STEM ecosystems in which multiple technological tools work together to support learning is another notable finding (Zhai et al., 2021). In these ecosystems, educational chatbots are the interactive interfaces with which students find their way through complex digital learning environments (Dale, 2016; Baker & Inventado, 2014). The merger of chatbots with digital learning ecosystems leads to the establishment of more efficient and accessible learning environments (Zhai et al., 2021).

Although the potential of digitally transformed STEM education is very strong, there are still important challenges to be solved (Luan et al., 2020; Margot & Kettler, 2019). In fact, efficient integration depends on not only providing teacher training but also designing lessons carefully (Ertmer & Ottenbreit-Leftwich, 2010). Regardless of how powerful the technology may be, teachers continue to play a crucial role in guiding students' use of digital tools and ensuring that these tools facilitate meaningful learning experiences (Tondeur et al., 2017). A further dimension of the discussion concerns the ethical issues that arise within digitally transformed learning environments (Williamson & Eynon, 2020; Porayska-Pomsta et al., 2023). AI tools, in particular, may compromise personal data privacy and give rise to concerns about irresponsible technology use. It is therefore vital that educational institutions embed digital technologies within ethical and responsible pedagogical frameworks (Holmes et al., 2021).

7. Conclusions

This research aimed to explore the changes in STEM education brought about by the use of digital technology and educational chatbots. The analysis of existing studies in this field reveals that digitization of education has led to a radical change in pedagogical and learning approaches in STEM fields. Learning environments enhanced by technology not only offer interactive, flexible, and learner-centered ways of educational experiences but also break traditional classroom boundaries.

A major outcome of the digital transformation of STEM education has been the emergence of blended learning spaces that integrate in-person teaching with online educational platforms. In such settings, students can access educational materials around the clock, which in turn promotes uninterrupted learning and self-directedness. Online resources like simulations, virtual labs, and interactive media engage students with scientific and mathematical content at a meaningful level, thereby supporting inquiry-based pedagogy and collaborative knowledge construction.

Within these digitally facilitated settings, educational chatbots present themselves as effective and supportive digital learning partners. Their capability to instantly respond, offer personalized clarifications, and continuously assist learning equip them to help students navigate the challenges posed by demanding STEM topics. Chatbots can assist learners both in the classroom and at home, complementing the teacher's work and fostering self-regulated learning. As natural language processing and conversational AI enter their maturity phase, their contribution towards personalized and large-scale learning scenarios will most likely increase.

Nevertheless, along with these possibilities, the embedding of digital technology and chatbots in STEM instruction also raises several issues. Questions around teacher professional development, technology infrastructure, data confidentiality, and AI system dependability need to be taken into account seriously. A digitally-based STEM teaching and learning environment can be set up successfully only when there is a balanced integration of technological advancement, sound instructional strategies, and robust institutional support.

In short, the paper's findings of this paper underscore the potential of educational chatbots and digital technologies as catalysts for adaptive, inclusive, and engaging STEM teaching and learning environments. Future research should investigate the practical implementation of chatbot-supported learning systems and evaluate their impact on students' performance through controlled and quantitative studies. As digital technologies continue to advance, the thoughtful integration of AI in education can play an instrumental role in shaping the future of STEM education and fostering more innovative, learner-centered educational ecosystems.

Compliance with ethical standards

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Disclosure of conflict of interest

The Authors proclaim no conflict of interest.

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