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AI-Enabled Virtual Labs in STEM Education: A Review of Adoption and Efficacy

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Abstract:
To cultivate future creative thinkers, it is essential to endorse STEM education that incorporates AI and other interactive learning technologies. Educational methodologies must evolve to more effectively engage students in the growing need for STEM (science, technology, engineering, and mathematics) disciplines. This study emphasizes the need of using AI and interactive technology to enhance STEM education and develop a new generation of skilled workers. AI-driven educational solutions provide tailored learning experiences by analyzing individual student performance and adapting content to meet their specific needs. Adaptive learning systems customize courses to meet each student's individual requirements, facilitating comprehension of challenging material at their own pace. AI facilitates immediate assessments and swift feedback to enhance learning and identify areas of difficulty. Virtual laboratories and augmented reality applications exemplify interactive educational technologies that provide immersive experiences, enhancing engagement with and accessibility to STEM disciplines. Students may participate in experiential learning and analytical reasoning inside a secure environment using virtual labs. Augmented reality applications facilitate user interaction with visual representations of scientific phenomena, therefore elucidating previously abstract concepts. Collaboration and problem-solving skills are augmented via the use of technology-enabled platforms. Students are encouraged to collaborate, share ideas, and learn from each other via online forums, virtual courses, and group projects. These platforms enable students to connect with mentors and professionals in STEM disciplines, facilitating their comprehension of the practical applications of STEM education and providing insights for their prospective professions. The emerging field of AI-STEM seeks to integrate AI into STEM education, facing the challenge of addressing instructional and learning requirements by merging diverse AI techniques with intricate educational elements. To comprehensively understand the applications of AI in STEM education, this This research conducted a thorough analysis of AI-STEM by analyzing 63 empirical papers from 2011 to 2025.

Keywords: STEM; Future Innovators; AI; Interactive Learning; Technologies

I. INTRODUCTION

An increasing number of individuals recognize that educating children in STEM (Science, Technology, Engineering, and Mathematics) disciplines is crucial for addressing the demands of the contemporary economy and labor market. A robust foundation in STEM disciplines equips students with analytical, deductive, and inductive reasoning skills, alongside technical expertise, essential for thriving in the contemporary job market, where technological progress propels economic expansion (Kennedy & Odell, 2014). STEM education is essential for addressing complex global issues such as climate change and public health crises, as well as for fostering national economic growth and facilitating technological advancements, beyond just enhancing individual career prospects (Marginson et al., 2013).

Notwithstanding the significance of STEM education, several challenges persist within the current system. Traditional teaching methods are ineffective when students lack enthusiasm or motivation in STEM subjects (Beede et al., 2011; Igbokwe et al., 2024). Moreover, marginalized groups encounter significant disparities in STEM education regarding both accessibility and quality, thereby intensifying existing labor inequalities (Mann & DiPrete, 2013). Moreover, students are ill-equipped for contemporary scientific and technical environments since curricula often lag behind the latest breakthroughs owing to the rapid pace of technological evolution (Langdon et al., 2011).

Educators and legislators are progressively using interactive learning technologies and artificial intelligence (AI) to address these challenges. By addressing each student's unique circumstances and learning preferences, AI has the potential to transform STEM classrooms (Holmes et al., 2019). Luckin et al. (2016) assert that AI-driven systems can rapidly evaluate student performance data and provide tailored feedback and resources to aid students in comprehending challenging subjects at their own pace. Furthermore, AI can manage administrative tasks, allowing educators to dedicate more time to developing engaging and interactive classes (Baker & Smith, 2019).

De Freitas and Neumann (2009) assert that STEM disciplines may be more effectively comprehended and used using interactive learning technologies such as gamification, simulations, virtual and augmented reality, and immersive learning experiences. These technologies may enhance student engagement and motivation by fostering a dynamic and interactive environment in which students can explore, experiment, and use their knowledge in practical contexts (Johnson et al., 2016). Bowers and Zazkis (2012) assert that the integration of artificial intelligence and interactive learning technologies may augment STEM education, enabling educators to provide a more relevant, customized, and effective STEM curriculum to pupils.

STEM education has several inherent issues; yet, there is optimism for the future via the integration of AI with interactive learning technologies. These technologies provide personalized and flexible learning experiences that meet diverse learning needs while enhancing student engagement and motivation (Mouboua, Atobatele & Akintayo, 2024; Ogborigbo et al., 2024). Educators may enhance STEM education and motivate the next generation of innovative thinkers and problem solvers by integrating these novel concepts into their curricula.

The Fourth Industrial Revolution (Industry 4.0) has significantly influenced education through the integration of emerging technologies such as artificial intelligence, automation, big data analytics, the Internet of Things (IoT), machine learning, robotics, and smart systems (Adib Rashid & MD Ashfakul Karim Kausik, 2024). These advancements have revolutionized the educational landscape by facilitating adaptive learning systems, enabling real-time data-driven decision-making, and implementing intelligent automation, so fundamentally altering the delivery and experience of education. Mhlongo et al. (2023) assert that the rapid advancement of digital transformation has resulted in learning occurring in technology-enhanced environments that seamlessly integrate virtual and physical spaces. Educators must use digital tools that promote engagement and cater to diverse student needs to leverage the growing integration of technology-enhanced learning with conventional classroom education.

II. Literature Review

The education sector has seen significant transformations throughout the years, transitioning from an emphasis on rote memorization to the integration of technology. Since its inception in the 2000s, artificial intelligence (AI) has transformed pedagogical methods and student learning processes. According to Huang & Qiao (2022), the primary objectives of artificial intelligence (AI) in education are twofold: firstly, to enhance the quality of teaching and student learning; and secondly, to educate students about AI and equip them with the necessary skills to engage with AI-powered systems. This study primarily focuses on the acceptance and use of AI by scientific educators as a pedagogical instrument.

Applications of artificial intelligence (AI) have increasingly been integrated into science education to enhance instructional delivery, stimulate student involvement in scientific research, elevate academic performance, and foster engagement. AI enhances scientific education by facilitating personalized learning experiences via adaptive learning platforms, intelligent tutoring systems (ITS), and AI-driven content recommendation systems. Squirrel AI and Century Tech are AI-driven platforms that provide students scaffolded learning experiences and real-time feedback, ensuring they get appropriate support throughout their scientific education. To effectively address student needs, educators may use these platforms to monitor progress, discern strengths and weaknesses, and then adjust lesson plans appropriately. (Olafare, 2024; Eyikorogha & Chigozie, 2024; Castellanos-Ch, Arias-Navarrete, & Palacios-Pacheco, 2020). Agbo et al. (2021) assert that AI-driven learning systems provide tailored resources and support to help students with diverse learning abilities bridge knowledge gaps. Consequently, AI-driven training enables instructors to transcend the traditional uniform approach, fostering a more tailored and adaptable learning environment that addresses diverse student needs and enhances long-term educational outcomes.

Moreover, AI fosters scientific inquiry by equipping students with tools to do data-driven experiments, evaluate ideas, and analyze data in real-time, alongside facilitating teaching. (Groenewald et al., 2024; Kumar et al., 2021; Srinivasan et al., 2022) Students may participate in interactive experiments in a safe environment using labs and artificial intelligence-driven simulations. According to the study of Mohammed Edali et al. (2024), this technique effectively addresses common challenges such as restricted laboratory resources, safety concerns, and accessibility limitations. Interactive digital experiences, such Labster and PhET simulations, enhance inquiry-based learning (Akamu et al., 2024; Diab et al., 2024; Salame & Samson, 2019). These platforms allow students to conduct experiments, acquire laboratory procedures, and understand intricate scientific topics without the constraints of a physical laboratory. Moreover, Google Teachable Machine (GTM) and analogous technologies enhance scientific exploration by enabling students to train machine learning models without requiring coding proficiency. This enables them to explore data categorization and pattern recognition influenced by artificial intelligence in their study (Herdliska & Zhai, 2023). By integrating advanced technology into the educational framework, these AI applications facilitate modern scientific inquiry. Ramadahan and Irwanto (2018) assert that AI-supported scientific inquiry enhances students' comprehension of scientific concepts, while also improving their problem-solving, critical-thinking, and laboratory skills.

Numerous academic fields have extensively used autonomous, adaptive, and efficient AI systems due to breakthroughs in computational technology and computer science. The interdisciplinary field of Artificial Intelligence in Education (AIEd) focuses on using AI to better the educational system, augment student learning, and assist educators in their teaching endeavors (Chen et al., 2020; Holmes et al., 2019; Hwang et al., 2020; Ouyang & Jiao, 2021). AIEd enhances instructional design and pedagogical improvement inside the classroom. This has been evidenced in multiple studies, including those that autonomously evaluate student performance (Wang et al., 2011; Zampirolli et al., 2021), oversee and monitor student learning (Berland et al., 2015; Ji & Han, 2019), and forecast which students are at risk (Hellings & Haelermans, 2020; Lamb et al., 2021). Secondly, AIEd facilitates student-centered learning by many means, such as adaptive tutoring, tailored resource suggestions, identification of learning gaps, and more methods (Kose & Arslan, 2017; Myneni et al., 2013; Ledesma & Garcia, 2017; Zhang et al., 2020; Liu et al., 2017). Third, AIEd offers opportunities to transform the educational system by highlighting the essential role of technology (Hwang et al., 2020), enhancing methods of information dissemination (Holstein et al., 2019; Yannier et al., 2020), and modifying the teacher-student relationship (Xu & Ouyang, 2022). Various kinds of artificial intelligence (AI) have been integrated into the classroom to enhance teaching and learning.

Progress in AI-STEM, a subdivision of AIEd, has similarly transformed STEM (science, technology, engineering, and mathematics) education. Research (Bybee, 2013; Pimthong & Williams, 2018) indicates that STEM education aims to improve students' abilities in higher-order thinking, critical thinking, problem-solving, and the investigation and application of multidisciplinary knowledge. Albedulhadi and Faisal (2021) and Walker et al. (2014) identify several advantages of integrating AI into STEM education. It may generate customized learning environments, assist educators in comprehending students' learning patterns, and autonomously assess their STEM learning outcomes. Nonetheless, the subject (e.g., instructor, student), information, medium, and environment are all interrelated components of the intricate system of STEM education (Rapoport, 1986; Von Bertalanffy, 1968).

To get superior STEM education, it is insufficient to only use AI technology; one must meticulously assess the intricate social, pedagogical, and environmental factors (Krasovskiy, 2020; Xu & Ouyang, 2022). Consequently, a significant challenge in AI-STEM lies in selecting and implementing AI methodologies that are effective for STEM education, considering the various factors (including the subject matter, data, and context) that influence effective teaching and learning (Castaneda & Selwyn, 2018; Selwyn, 2016). A meticulous examination and analysis of the many elements of AI-STEM from a systemic perspective is crucial for cultivating a thorough understanding of the integration of AI technology inside STEM educational environments.

The field of AIEd has garnered significant attention over the last decade (Chen et al., 2020; Holmes et al., 2019; Hwang et al., 2020; Ouyang et al., 2022). Despite existing literature on AIEd, most of it has a technical perspective, focusing on its trends, applications, and effects (Chen et al., 2020; Tang et al., 2021; Zawacki-Richter et al., 2019). Between 2011 and 2021, a total of eighteen studies examining the literature on AIEd were identified (see Fig. 1). Several AIEd reviews have focused on particular domains of education, levels of study, and contexts, including mathematics education (Hwang & Tu, 2021), language education (Liang et al., 2021), programming education (Le et al., 2013), medical education (Khandelwal et al., 2019; Lee et al., 2021), and special education (Drigas & Ioannidou, 2012). A research by Zawacki-Richter et al. (2019) examined AIEd in higher education and identified four technical applications of artificial intelligence: intelligent tutoring systems, adaptive systems and customisation, profiling and prediction, and assessment and evaluation. Liang et al. (2021) conducted an examination into the use of artificial intelligence (AI) in language classes, aiming to delineate the role and extent of AI research in this domain, including research methodology and sample populations.

Drigas and Ioannidou's (2012) research on AIEd in special education included an overview of AI applications designed for students with disabilities, including dyslexia, autism spectrum disorder, and difficulties with reading and writing.

III. Methodology

The Function of Artificial Intelligence in STEM Education

Personalized learning experiences and real-time evaluations and feedback might be created by integrating artificial intelligence (AI) in STEM education, which could completely transform teaching and learning (Atobatele, Akintayo & Mouboua, 2024). These advancements meet the varied requirements of students, boost participation, and raise the quality of education. Artificial intelligence-enabled personalized learning experiences have the potential to greatly improve students' academic performance by responding to their unique requirements. An important part of this strategy is adaptive learning systems, which use artificial intelligence algorithms to read student records and change the curriculum appropriately. By analyzing each student's data, these systems can tailor STEM learning materials to help each student overcome their unique set of challenges. According to Holmes et al. (2019), students' performance and happiness may be enhanced via the use of adaptive learning technology.

As an example, systems powered by AI may track students' development in real-time by constantly gathering data on their reactions and interactions. By using this data, the difficulty level of exercises may be adjusted dynamically. This way, pupils won't be bored by too simple information or overwhelmed by too tough stuff. Individualized lessons like this keep students interested and engaged, which is essential for mastering difficult STEM topics (Kulik & Fletcher, 2016). An inclusive learning environment may be created by using AI to provide personalized learning experiences for students with different abilities and learning styles.

Essential for successful STEM education, AI allows for real-time evaluations and feedback in addition to customized learning experiences. Because they enable students to swiftly comprehend their errors and implement required adjustments, immediate feedback mechanisms are a potent instrument for improving student learning (Okunade, et. al., 2024, Oladimeji & Owoade, 2024). Students' performance and memory recall may be greatly enhanced with the use of timely feedback, according to research (Shute, 2008). Artificial intelligence systems can quickly assess student work and provide immediate comments, allowing them to quickly fix their mistakes and reinforce what they've learned.

Furthermore, AI's capacity to detect and rectify knowledge gaps is priceless when it comes to STEM education. Artificial intelligence can identify student weaknesses and provide specific support via ongoing evaluation. To do this, we look for trends in the data on how well students are doing to identify which ideas or abilities need further work. Upon detection, the AI system may provide students with further materials, practice problems, or other explanations to aid in their progress toward mastery (Luckin et al., 2016). A strong grounding in STEM disciplines is crucial for students' future success, and AI can help them achieve this by filling in learning gaps as they arise.

Intelligent tutoring systems (ITS) are one way AI is being used in STEM education. By customizing lessons and comments to each student's unique strengths and weaknesses, these programs mimic the effects of private coaching. By providing students with step-by-step guidance, ITS may engage them in interactive problem-solving exercises. Studies have shown that ITS can enhance student learning just as much as human instructors, especially in the areas of science and mathematics (VanLehn, 2011). Students are able to improve their problem-solving abilities and get a more thorough grasp of STEM ideas with the aid of ITS's individualized guidance.

AI is also helpful for educators since it automates paperwork and gives data on how well students are doing in class. Educators are free to devote more time to lesson planning and individualized coaching when AI takes over grading and data analysis. In addition, reports provided by AI may provide useful information about patterns in the whole class, allowing instructors to pinpoint typical difficulties and modify their methods of instruction appropriately (Baker & Smith, 2019, Mouboua & Atobatele, 2024). Students and teachers alike may reap the advantages of a more comprehensive approach to STEM education when AI-driven individualized learning, real-time evaluations, and teacher assistance are all combined.

Ultimately, AI plays a game-changing role in STEM education by means of real-time evaluations and customized learning paths that boost student interest and performance. Continuous assessment finds and fills in knowledge gaps, while adaptive learning systems and quick feedback systems personalize lessons for each student. A more effective, inclusive, and engaging learning environment will be created by integrating AI into STEM education as it continues to advance. This will prepare students to become innovators and problem solvers of the future.

Technology-Enabled, Interactive STEM Education

Interactive learning technologies have revolutionized STEM education by providing novel tools that engage students and improve their comprehension of intricate subjects. Virtual labs and augmented reality (AR) apps are distinguished by their capacity to provide immersive and interactive educational experiences. Virtual labs provide a safe setting for students to do experiments and investigate scientific topics without the limitations of a real laboratory. This adaptability facilitates continual practice and experimentation, which is especially advantageous in disciplines such as chemistry and physics, where practical experience is essential for comprehension. Virtual laboratories allow students to adjust variables, examine results, and cultivate a more profound comprehension of scientific concepts. Studies indicate that virtual labs may markedly improve student learning by fostering active involvement and critical thinking (De Jong, Linn, & Zacharia, 2013).

The advantages of risk-free experimenting in virtual laboratories are considerable. Students may engage with dangerous materials or intricate processes without the inherent risks, enabling them to concentrate on learning rather than safety issues. This setting fosters inquiry and invention, allowing students to make errors and learn from them without real-world repercussions. Research indicates that students using virtual laboratories have enhanced problem-solving abilities and a superior understanding of scientific principles relative to their counterparts employing conventional techniques (Rutten, van Joolingen, & van der Veen, 2012).

Virtual laboratories enable a secure environment for experimentation while enhancing experiential learning and analytical reasoning. Through participation in virtual experiments, students may use theoretical knowledge in realistic contexts, therefore connecting abstract ideas with real-world applications. This experiential learning method cultivates a profound comprehension of STEM disciplines and motivates students to engage in critical analysis of the scientific process. Research indicates that virtual laboratories may improve student motivation and engagement in STEM, resulting in increased success and retention rates (Makransky et al., 2019).

Augmented reality (AR) apps serve as a potent instrument in STEM teaching, providing interactive visuals that make abstract ideas more concrete. Augmented reality superimposes digital information onto the actual environment, enabling students to see scientific processes in real time. Augmented reality may exemplify chemical structures, display electromagnetic waves, or imitate biological processes. These interactive visualizations assist students in comprehending intricate topics by offering tangible representations of abstract notions. Studies demonstrate that augmented reality enhances student comprehension and retention of knowledge by making learning more engaging and intuitive (Ibáñez & Delgado-Kloos, 2018).

The use of augmented reality in education significantly improves student engagement and motivation. By integrating interactive components into classes, AR fosters a more dynamic and immersive educational experience. Students may engage with digital information actively, manipulating virtual objects and watching their behavior inside a simulated environment. This interaction cultivates a profound engagement with the content and promotes active learning. Research indicates that students using AR apps have increased engagement and heightened interest in STEM disciplines relative to those employing conventional approaches (Bacca et al., 2014).

Furthermore, augmented reality aids in making abstract ideas tangible, hence enhancing understanding. For example, viewing intricate mathematical functions or physical forces using augmented reality helps elucidate these ideas and enhance comprehension. Augmented reality facilitates the development of mental models in pupils by offering a visual and interactive environment that improves cognitive processes. Studies have shown that augmented reality (AR) enhances spatial awareness and conceptual comprehension, resulting in improved academic achievement in STEM disciplines (Wu, Lee, Chang, & Liang, 2013).

In conclusion, interactive learning technologies such as virtual labs and augmented reality apps are transforming STEM education by offering immersive, hands-on experiences that improve student engagement and comprehension. Virtual laboratories provide a secure and adaptable setting for experimenting, fostering critical thinking and problem-solving abilities. Simultaneously, augmented reality apps animate abstract ideas, enhancing the engagement and accessibility of learning. As these technologies progress, they provide significant potential for cultivating future innovators and enhancing STEM education.

Co-Learning Platforms

Collaborative learning platforms are essential for advancing STEM education, including online forums, virtual classrooms, group projects, and cooperative problem-solving. These platforms promote collaboration, enable idea exchange, link students with mentors and industry experts, and cultivate vital teamwork skills, therefore augmenting the practical applications of STEM knowledge.

Online forums and virtual classrooms are essential elements of collaborative learning platforms, providing a dynamic environment for students to participate in cooperation and exchange ideas. These platforms provide a venue for students to engage in discussions, pose inquiries, and get response from peers and professors instantaneously. The interactive characteristics of online forums cultivate a feeling of community and cooperation, which is vital for the proper comprehension of intricate STEM disciplines. Hrastinski (2009) asserts that online learning environments augment student involvement and interaction, resulting in heightened engagement with the topic and enhanced learning results.

Virtual classrooms facilitate connections between students and mentors or industry experts, fostering chances for mentoring and professional advancement. Students may get insights from experts and practitioners in their industry via virtual guest lectures, webinars, and interactive sessions. This experience enhances students comprehension of STEM jobs and offers crucial networking chances for their future professional endeavors. Research conducted by Cheng, Wang, Moormann, Olaniran, and Chen (2012) demonstrates that virtual classrooms promote significant connections between students and experts, enhancing the overall educational experience.

Group projects and collaborative problem-solving endeavors are a fundamental element of collaborative learning systems. These exercises need students collaborating to resolve intricate challenges, reflecting the cooperative essence of actual STEM professions. Collaborative projects facilitate the development of essential collaboration competencies, including communication, coordination, and conflict resolution. Furthermore, collaborative problem-solving fosters critical thinking and creativity as students learn to examine issues from several viewpoints and integrate their knowledge to devise unique solutions. Research conducted by Johnson, Johnson, and Smith (2007) indicates that cooperative learning significantly enhances student performance and social skills.

Group projects not only promote collaboration but also provide students practical, real-world applications of STEM knowledge. Engaging in initiatives that tackle real-world issues enables students to see the applicability of their academic pursuits to daily life and prospective jobs. This pragmatic application of information not only solidifies theoretical ideas but also augments students' problem-solving skills and equips them for the requirements of the STEM industry. The study conducted by Springer, Stanne, and Donovan (1999) underscores the beneficial effects of collaborative learning on student performance and retention in STEM disciplines.

The use of collaborative learning platforms in STEM education fosters inclusion by addressing various learning styles and requirements. These platforms enable students to study at their own speed, access resources as required, and interact with the subject in a manner that aligns with their own preferences. This adaptability makes STEM education more attainable for a broader spectrum of pupils, including those who may find conventional teaching techniques challenging. Means, Toyama, Murphy, Bakia, and Jones (2010) assert that online and mixed learning settings provide substantial benefits for different learners, resulting in enhanced educational results.

IV. Expanding Opportunities for All Students in STEM Fields

The promotion of STEM education via AI and interactive learning technologies is essential for improving accessibility and inclusiveness, engaging underprivileged and distant students, and fostering a diverse talent pool in STEM fields. Equitable access to learning via technology and the mitigation of the educational gap are crucial for guaranteeing that all students, irrespective of their geographic or socio-economic circumstances, may attain high-quality STEM education. Moreover, promoting diversity in STEM is essential for stimulating innovation and meeting the demands of a swiftly changing global society.

Engaging underprivileged and distant students presents a considerable problem in conventional STEM teaching. Nonetheless, technology has the capacity to provide equitable learning chances, guaranteeing that students in rural or economically deprived regions may access identical resources and educational experiences as their metropolitan peers. Online learning platforms, virtual classrooms, and digital materials facilitate student engagement in STEM education irrespective of geographical constraints. Tomlinson and Whittaker (2013) assert that technology-mediated learning settings may successfully connect distant and urban students, ensuring fair access to educational opportunities and resources.

The use of AI in STEM education significantly improves accessibility by providing individualized learning experiences customized to the requirements of each learner. AI-driven adaptive learning systems evaluate student performance data to tailor training, guaranteeing that each student has the necessary support for success. This tailored method facilitates equity for underprivileged kids who may need extra support to comprehend intricate STEM subjects. Baker and Inventado (2014) demonstrate the efficacy of adaptive learning technology in enhancing student performance and diminishing educational inequalities.

Bridging the educational gap necessitates solving the digital divide, guaranteeing that all students possess access to requisite technology and internet connection for participation in online learning. Initiatives like supplying affordable or complimentary gadgets, enhancing internet connectivity in underprivileged regions, and delivering technical assistance are essential for surmounting these obstacles. Research by Warschauer and Matuchniak (2010) underscores the need of tackling the digital gap to guarantee fair access to STEM education and avert the worsening of existing inequities.

Fostering a broad pool of STEM talent is crucial for promoting innovation and tackling the intricate issues of contemporary society. Diversity in STEM fosters a multitude of viewpoints and concepts, resulting in more innovative and efficient solutions. Inclusive STEM education initiatives seek to involve students from many backgrounds, particularly those historically underrepresented in STEM disciplines, including women, minorities, and those with disabilities. The National Science Foundation (2017) asserts that enhancing diversity in STEM is essential for sustaining a competitive advantage in global innovation and for ensuring that the STEM workforce reflects the demographic diversity of the community it serves.

Strategies for inclusive STEM education include the development of culturally relevant curriculum, the promotion of mentoring and role models, and the execution of programs aimed explicitly at underrepresented groups. Programs that promote girls' engagement in STEM disciplines, such as Girls Who Code, have effectively augmented female representation in technological sectors. Research conducted by Master, Cheryan, and Meltzoff (2016) indicates that exposure to female role models in STEM significantly enhances girls' enthusiasm and self-efficacy in these disciplines.

Mentorship and role models are essential in cultivating a feeling of belonging and desire among minority students in STEM fields. Linking students with mentors who possess like backgrounds and experiences may provide significant insight, support, and encouragement. Crisp and Cruz (2009) demonstrate the beneficial effects of mentoring on the academic and professional advancement of minority students in STEM disciplines.

Establishing inclusive learning environments necessitates the provision of accessible instructional approaches and resources for all students, including those with impairments. This include the use of assistive technology, the provision of materials in various forms, and the implementation of Universal Design for Learning (UDL) principles to address varied learning requirements. Research conducted by Rose, Meyer, and Hitchcock (2005) substantiates the efficacy of Universal Design for Learning (UDL) in fostering inclusive education and enhancing results for all students.

In summary, advancing STEM education via AI and interactive learning technologies is essential for improving accessibility and inclusiveness, engaging underprivileged and distant students, and fostering a diverse pool of STEM talent (Atobatele, Kpodo & Eke, 2024; Owoade & Oladimeji, 2024). By offering equitable educational opportunities, closing the educational gap, and using inclusive pedagogical practices, we can guarantee that all students have the opportunity to excel in STEM disciplines, fostering creativity and tackling the intricate difficulties of contemporary society.

V. The theoretical structure and the research process

General system theory (GST) is a theoretical framework positing that the universe consists of many biological systems characterized by dynamically interacting constituents and interrelationships among them (Rapoport, 1986; Von Bertalanffy, 1950). The fundamental tenet of GST is that a system transcends the mere aggregation of its components, embodying a higher whole than the sum of its individual parts (Drack & Pouvreau, 2015; Von Bertalanffy, 1968). To thoroughly comprehend the intricate nature and overarching principles of systems, GST emphasizes the holistic principle of the system to discern its internal components, their functional interrelations, and the external influences affecting the system (Crawford, 1974). The theoretical framework of General Systems Theory (GST) has been extensively used across many domains to examine numerous system types, including physical, biological, social, and educational systems (Drack & Pouvreau, 2015; Kitto, 2014).

Chen and Stroup (1993) proposed using GST as a foundational theoretical framework to direct the reform of scientific education, emphasizing the integration of the science curriculum to prevent the segregated study of physics, biology, and chemistry.

In accordance with this mindset, we contend that GST offers a novel, comprehensive framework for comprehending the integration of AI technology inside STEM education. From the standpoint of GST, AI-STEM may be seen as an organic system with five fundamental elements: subject, information, medium, environment, and technology (Von Bertalanffy, 1968) (see Fig. 1).

The term 'subject' refers to individuals inside an educational system, where various roles, such as teacher and student, engage in continuous and adaptive interactions. Secondly, information pertains to knowledge disseminated and built among individuals within an educational framework, including learning content, course materials, and knowledge artifacts. Third, the medium serves as the conduit for transmitting information and linking subjects inside the system. The environment acts as a foundational setting inside an educational system, impacting the operation of the whole system. Fifth, technology (e.g., AI approaches) often manifests as an external factor influencing the operations of the educational system. Based on GST, the incorporation of AI as an external technological component inside an educational system, such as STEM, is a multifaceted process that impacts other system components (i.e., topic, information, medium, environment) and the interrelations among them. The GST framework (refer to Fig. 1) elucidates the many components and their interconnections within the AI-

STEM system, offering a comprehensive perspective on the integration of AI technology in STEM education.

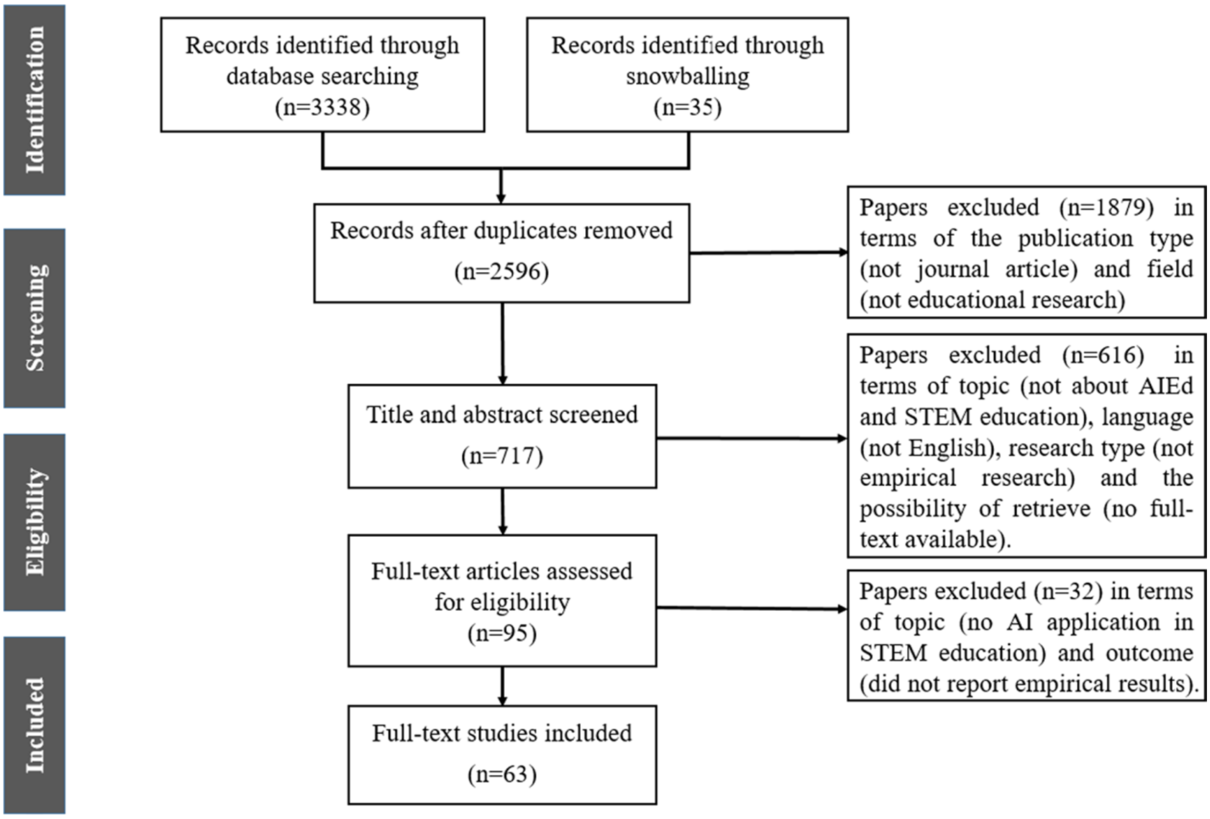

Fig. 1 The integration of technology in an educational system from the GST perspective

VI. Issues and Considerations

Advancing STEM education via AI and interactive learning technology offers several potential to augment student engagement and cultivate future innovators. This strategy has several obstacles and issues that must be addressed to guarantee its successful implementation and sustainability. A key priority is safeguarding data privacy and security. The incorporation of AI in education entails the aggregation and examination of extensive student data to tailor learning experiences. This presents substantial privacy concerns, since sensitive information requires safeguarding from illegal access and exploitation (Atobatele & Mouboua, 2024; Mouboua, Atobatele & Akintayo, 2024). Effective measures to manage these risks include the implementation of strong data encryption, the establishment of stringent data access restrictions, and the assurance of compliance with relevant data protection rules (Williamson, 2017). Furthermore, educators and administrators must provide transparency with students and parents on data gathering procedures and the safeguards used to protect their information.

A further difficulty is mitigating excessive dependence on technology. Although AI and interactive technologies may significantly improve the learning experience, there is a danger that they may eclipse conventional teaching techniques and human contact, which are essential for comprehensive education. It is crucial to achieve a balance in which technology serves as a supplementary tool rather than a substitute for conventional educational methods (Luckin et al., 2016). This equilibrium guarantees that students gain from technology progress while also acquiring the essential critical thinking, problem-solving, and interpersonal skills derived from human interactions.

Educating instructors to use new technology proficiently is an essential factor. Educators must be sufficiently equipped to incorporate AI and interactive technologies into their classrooms (Hina & Dominic, 2020; Williamson, Bayne & Shay, 2020). This preparation necessitates extensive professional development programs that both acquaint instructors with new technology and provide them with techniques to properly integrate these tools into their teaching practices. Professional development must emphasize both the technical proficiency in AI and interactive technologies and the pedagogical strategies to use these tools for improving learning outcomes (Zhou et al., 2018).

Incorporating technology into established curriculum might sometimes be difficult. Curriculum creation must be flexible to include new technologies in accordance with educational standards and learning goals (Adıgüzel, Kaya & Cansu, 2023; Bozkurt, 2023). This process includes changing lesson plans, creating new teaching resources, and consistently evaluating the efficacy of technology integration (Hsu, 2015). Educators need assistance from administrators and politicians to guarantee that curricular modifications are adequately planned and funded.

Moreover, the expense associated with the implementation of AI and interactive technologies might be exorbitant for several educational institutions. Educational institutions must provide resources for technology, software, and continuous maintenance, thereby burdening constrained budgets. To resolve this problem, universities may pursue collaborations with technology firms, apply for grants, and investigate creative financing mechanisms to enhance the accessibility of these technologies (Shin & Kang, 2015).

Guaranteeing fair access to technology is a substantial problem. The digital gap continues to hinder successful implementation, since students from disadvantaged backgrounds often lack access to essential technical tools. Educational institutions must strive to provide equitable access to technology for all students, which may include supplying devices, facilitating internet connectivity, and establishing inclusive learning environments that address varied requirements (Smith, 2016). Closing this gap is essential for guaranteeing that all students may take advantage of progress in educational technology (Al-Hamad et al., 2023; Mahapatro, 2021).

In conclusion, while AI and interactive learning technologies has significant potential to revolutionize STEM education, it is imperative to address the related problems and concerns for their effective application. Critical steps in this process include ensuring data privacy and security, avoiding excessive dependence on technology, delivering effective training for educators, integrating technology into existing curricula, managing costs, and promoting equitable access (Okunlaya, Syed Abdullah & Alias, 2022; Saaida, 2023; Vrontis et al., 2023). By tackling these difficulties, educational institutions may fully use new technologies to engage and equip future innovators, therefore improving the quality and diversity of STEM education.

Prospects for STEM Education in the Future

The promotion of STEM education using AI and interactive learning technologies is set to substantially impact the educational environment. Future trends and prospective improvements are poised to significantly improve student learning and engagement in STEM disciplines (Almusaed, et. al., 2023; Kangiwa, et. al., 2024; Onesi-Ozigagun, et. al., 2024). A prominent developing trend is the growing complexity of AI-driven adaptive learning systems. These systems use machine learning algorithms to scrutinize extensive data on student performance, allowing highly individualized learning experiences. By constantly adjusting to the requirements and advancements of individual students, these systems may provide customized training that enhances learning results (Holmes et al., 2019). As AI technology progresses, we may anticipate more accurate and effective adaptive learning systems that accommodate a variety of learning styles and speeds.

A potential domain is the development of immersive technologies, including virtual reality (VR) and augmented reality (AR). These technologies provide distinct chances for practical, experience learning that may make abstract STEM topics more concrete and accessible. For instance, virtual reality may immerse students in simulated labs, enabling them to do experiments in a safe setting, while augmented reality can superimpose interactive representations onto the physical world to enhance students' comprehension of intricate scientific concepts (Ibáñez & Delgado-Kloos, 2018). As these technologies become more accessible and prevalent, their incorporation into STEM education is expected to intensify, offering more enriching and engaging learning experiences.

Progress in artificial intelligence is facilitating the development of intelligent tutoring systems and virtual mentors. AI-driven solutions provide immediate assistance and tailored feedback to students, effectively addressing learning deficiencies and enhancing comprehension in real-time (Barkley & Major, 2020; Buentello-Montoya, Lomelí-Plascencia & Medina-Herrera, 2021; Onyema, 2020). This capacity is especially beneficial in STEM education, since prompt assistance helps save students from lagging in difficult courses (Woolf et al., 2013). As artificial intelligence advances, these tutoring systems will progressively emulate the nuanced instruction of human tutors, providing scalable options for individualized education.

The potential for merging AI and interactive technology with collaborative learning systems is substantial. These platforms may enhance collaboration and idea exchange among students, linking them with classmates, mentors, and industry experts worldwide. Utilizing AI to assess group dynamics and provide insights into efficient cooperation, these platforms may improve the quality and effectiveness of group projects and problem-solving endeavors (Kumar et al., 2020). This worldwide connectedness and cooperation will equip students for the more interconnected and multidisciplinary characteristics of contemporary STEM employment.

To prepare for the future of STEM education, it is essential to prioritize the creation of comprehensive professional development programs for instructors. Educators need continuous training to proficiently integrate innovative technology into their courses and to be informed about the latest educational advancements. This training must prioritize both technical expertise and pedagogical methods for using technology to improve student engagement and learning (Ertmer & Ottenbreit-Leftwich, 2010).

Alongside teacher training, educational institutions must emphasize infrastructure development to facilitate the extensive use of new technologies. This encompasses investment in high-speed internet access, modern technology, and secure data management systems to provide fair access to sophisticated learning resources for all students (Selwyn, 2016). Mitigating the digital gap is crucial for guaranteeing that the advantages of AI and interactive learning technologies are available to all students, irrespective of their socioeconomic status.

VII. Conclusion

The amalgamation of AI with interactive learning technologies signifies a substantial transformation in STEM education, providing revolutionary prospects for student engagement and equipping them for future advancements. The examination of these technologies uncovers some critical conclusions about their influence on the educational scene. AI-driven adaptive learning systems provide customized educational experiences, modifying training to accommodate specific student requirements and providing immediate feedback to rectify learning deficiencies. Interactive technologies, like virtual reality (VR) and augmented reality (AR), improve learning by facilitating risk-free experimenting and visualizing intricate scientific concepts, thereby making abstract ideas more comprehensible and concrete. Collaborative learning platforms use these technologies to promote cooperation, link students with mentors and industry experts, and enable worldwide collaboration, therefore equipping students for multidisciplinary and linked STEM jobs.

To fully harness the promise of these breakthroughs, it is essential to confront numerous problems, including guaranteeing fair access to technology, successfully educating educators, and merging innovative approaches with established practices. Commitment to these domains is crucial for optimizing the advantages of AI and interactive technologies, enabling equitable access to high-quality STEM education for all students. The ongoing development of AI and interactive learning technology forecasts significant advances in STEM education. Emerging developments, including advanced adaptive learning tools, improved immersive experiences, and intelligent tutoring systems, are expected to further refine and enrich educational procedures. It is essential to prioritize the preparation of educators for the proper integration of modern technologies while addressing infrastructural and equity concerns to guarantee that all children can benefit from these breakthroughs.

Ultimately, engaging and equipping future innovators with technology requires a deliberate effort to use the revolutionary capabilities of AI and interactive learning technologies. By cultivating a climate conducive to the successful utilization of these technologies, educators may augment student engagement, increase learning outcomes, and equip the forthcoming generation of STEM leaders. The pursuit of a more creative and successful STEM education system is continuous, requiring sustained commitment and adaptability to the changing technological environment. Adopting these changes with a progressive mindset will be essential in cultivating a future where STEM education enables all students to realize their full potential and make significant contributions to the realm of innovation.

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