Augmented Reality Applications in STEM Education: A Review

Fredrick Ishengoma, Lucian Ngeze, Placidius Ndibalema

Abstract: **In recent years, augmented reality (AR) technologies have garnered more attention as a potential game changer for teaching and learning in science, technology, engineering, and mathematics (STEM) education. AR uses computer vision and wearable technology, allowing users to participate in an increasingly realistic and interactive world by layering digital content over physical reality. This paper looks comprehensively at various aspects of AR applications in STEM teaching and learning, offering a reasoned analysis of the opportunities and problems faced in adopting this new technology. The study argues that AR can promote student engagement and learning in a wide range of fields through various application examples. However, the barriers to widespread usage have long been the complexity of technology, lack of funds, and the issue of equity. Alongside these constraints come various strategies for surmounting them. In addition, the paper identifies areas for future research and development, such as novel pedagogical approaches as ways of teaching and inclusive access to AR technology, as well as benefiting from user-friendly authoring tools.**

***Keywords*: Augmented Reality, STEM Education, Technology Integration, Educational Innovation, Learning Outcomes**

I. Introduction

In recent years, much attention has focused on augmented reality (AR) technology, which can potentially find practical applications in diverse disciplines [1]. Drawing from progress made in computer vision, graphics, and wearable technology, AR delivers a captivating and interactive experience by superimposing digital content over reality in real time [2, 3]. This capability has sparked an interest in using AR for teaching and learning in science, technology, engineering, and mathematics (STEM) fields [4].

One of the barriers to the old-school approach to teaching STEM subjects is being able to capture students' attention and help them understand complex things clearly [5]. Moreover, STEM education faces challenges that affect a student's participation and how well they perform. One is the abstractness of STEM concepts, which needs to be more easily understood by students trained only in traditional ways [5].

Furthermore, numerous demographic disparities exist across gender and race lines in STEM entry and continuing participation [6]. Traditional lecture-based teaching methods faces challenges to meet the multiple learning styles of students, exacerbated by diversity in STEM areas, and have the side effect of dull students and lowering achievement [7].

AR represents a technology offering to solve many problems faced by STEM education [2, 3]. By placing digital content on real-world objects, AR offers a new way to see abstract principles better, simulate things as they are, and supply practical lessons [8]. Studies have demonstrated that STEM has the potential to provide an immersive, interactive approach that improves learning, student engagement, motivation, and understanding of STEM subjects [2, 8].

In recent years, integrating AR technology into educational settings has increased interest [2, 4, 5]. Different subject educators and researchers have applied AR in various fields, from human anatomy and biology to physics and engineering [1, 6]. Virtual dissections and interactive simulations are examples of how these applications have been incorporated into teaching [5, 7]. It all aims at enhancing the student's learning experience and achievement. As well, improvements in mobile devices like smartphones and tablets have made AR more accessible and affordable [9]. This is opening up even more ways to use these new educational tools.

Although studies on AR used for STEM education have increased [4–8], most of these studies are in silo domains and there is still a lack of comprehensive systematic reviews of the existing literature. This review aims to fill that gap by offering a summary of where AR is now in STEM education. It examines its effectiveness and challenges and points to where this current trend might be headed. The purpose of this review is to: Specifically, the goals of this study are:

1. Explore the various applications of AR in STEM education and evaluate the effectiveness of AR in enhancing student engagement, motivation, and learning outcomes.
2. Identify challenges and limitations associated with the integration of AR in educational settings.
3. Discuss the potential of AR to address the diverse needs and preferences of learners in STEM education.

By identifying the strengths and weaknesses of merging AR with STEM education, the study will allow teachers, researchers, and policymakers to consider AR as a medium for learning and teaching. The study also identify gaps and research areas that need further investigation to inform evidence-based interventions and support future intervention design for AR-based learning.

The rest of the paper is structured as follows: Section 2 provides related works, and Section 3 presents the methodology used in the study. Section 4 presents the study’s findings, and Section 5 presents the discussion. Policy implications of the study are presented in Section 6, and the study concludes with a conclusion and future work in Section 7.

II. RELATED WORKS

In recent years, there has been a significant surge of interest and research in the use of augmented reality AR in STEM education, as innovators and educators have started to explore the potential of these technologies to transform learning experiences.

One of the promising application of AR is educational biology: Numerous research studies have shown great promise in using this technology to help with anatomy and physiology education, often leading to improved student learning outcomes and learning engagement [5, 11, 14]. For example, AR has been used to explore the human skeletal system with [31], which reported a significant improvement in their spatial ability, knowledge acquisition, and student motivation. In another study [32], AR was applied to the human circulatory system to better understand this organ's mechanism. Improvement was seen in learning achievements and engagement by the students.

In another context of physics education, AR has been used for the visualization of abstract concepts through interaction to help students better understand various physical phenomena. For example, the study [33] used AR to create an educational environment for teaching optics. The study noted that students showed better conceptual understanding, problem-solving skills, and motivation. Similarly, [34] used AR to teach kinematics and noted student's improvement in the understanding of spatial visualization and conceptual knowledge.

Literature shows that, as AR allows a display of three-dimensionality, it is beneficial for subjects such as chemistry education, for instance, in a combination of text and images to visualize the molecular structure of particles and illustrate chemical reactions [12, 16]. Several recent research studies have shown that AR can help students learn and engage when teaching organic chemistry, improving their spatial ability and ability to visualize molecular structures, as well as their motivation [6, 12, 16]. Another study [35, 36] also demonstrated that AR-enhanced teaching of stoichiometry can significantly increase students' understanding and problem-solving ability.

There have recently been a number of empirical studies suggesting benefits for student learning and engagement especially in learning abstract concepts [21, 30, 37, 38]. [37], For instance, AR-based geometry teaching was compared with traditional chalkboard-based methods and found that AR significantly enhanced students' spatial reasoning, conceptual understanding, and motivation. [38] explored the use of AR in teaching algebra and were also able to report positive impacts on students' problem-solving ability and engagement.

Moreover, AR has also been used in engineering education for the design, prototyping, and modelling of complex systems, and recent empirical studies have reported its positive impact in promoting creativity and collaboration skills among learners [39, 40]. For example, [39] developed an AR-based learning environment for teaching mechanical engineering design and found that their students' design thinking, creativity, and collaboration skills were improved. Likewise, [40] investigated the use of AR in teaching civil engineering concepts and observed the positive impact on improving students' abilities in spatial visualization and understanding of structural analysis.

III. METHODOLOGY

The study employs the literature synthesis methodology, and the search was done on major electronic databases, including PubMed, Scopus, Web of Science (WOS), and Information Science and Technology Abstracts (LISTA). The search strategy employed a combination of terms, synonyms, and variations with boolean operators (AND, OR) in the search string, which aids in the precise search of the relevant literature. The literature considered was peer-reviewed scholarly contributions that were published from January 1, 2015, to June 31, 2024.

The relevance of the topics chosen for the study was reaffirmed by selecting from a corpus of literature that explicitly included resources on augmented reality in STEM. To keep the study relevant and readable, all of the articles for the study were limited to those published in the English language. In keeping with the inclusion requirements, articles that were found to be in compliance were included in the review.

On the other hand, non-compliance articles were excluded. Sources that were not peer-reviewed and non-academic publications, were excluded to ensure the integrity of the studies. The grey literature, including but not limited to reports and blog posts, were also excluded from the sources used in the research to concentrate on peer-reviewed academic research. Furthermore, the literature that were not specific to the aim of the research, which is augmented reality in STEM, was also excluded.

The data extraction process took place after the screening phase to summarize and interpret the critical information present in each included article. Categories were derived through a thematic analysis of the literature. To ensure that only the most significant and recurrent themes were included, a threshold was established. Themes were selected based on their frequency across the reviewed studies and their relevance to the central issues identified. Specifically, categories appearing in more than 25% of the literature were considered for inclusion.

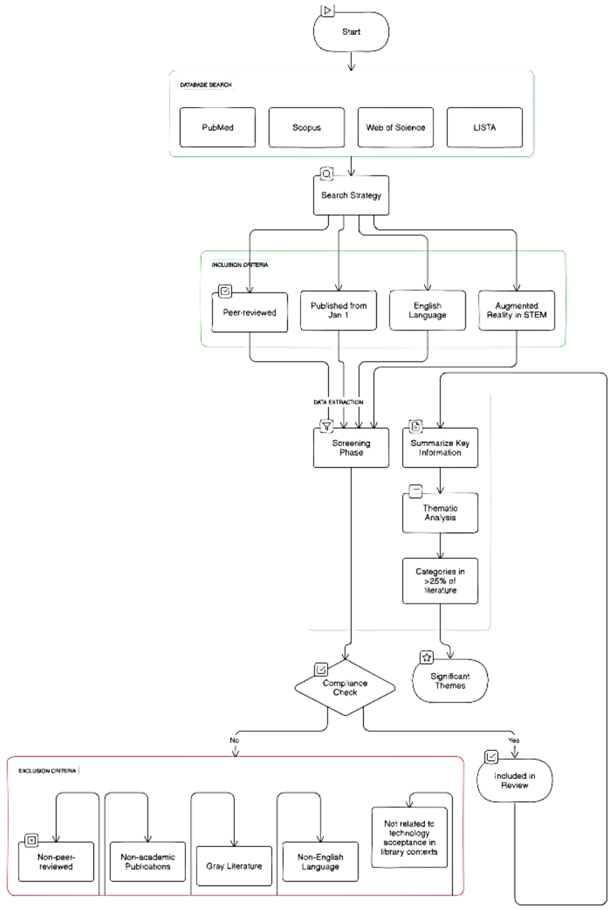

Figure 1: Methodology employed in this study (*source:* authors' own work)

When the two researchers did not agree about an issue, a third expert was asked for his view. After an assessment of 180 articles, 42 were found acceptable for this study. Those pieces meeting the inclusion criteria were coded by the researchers on their own. The data was then entered into Microsoft Excel. First, 10 randomly selected articles were coded by the two researchers separately in order to determine coding reliability. Inter-rater reliability was calculated as 0.93 according to Cohen's kappa analysis.

After confirming the coding reliability through repeated comparison checks, the remaining articles were coded separately by the two researchers. After the coding process had finished, the researchers solved their disagreements over codes through mutual discussion of the coding scheme. The data were analyzed using the content analysis method. Content analysis is a method that includes text organization, categorization, comparison, and theorizing [29]. Categories were derived through a thematic analysis of the literature. To ensure that only the most significant and recurrent themes were included, a threshold was established. Themes were selected based on their frequency across the reviewed studies and their relevance to the central issues identified. Specifically, categories appearing in more than 25% of the literature were considered for inclusion [30].

IV. FINDINGS

The findings from the systematic literature review on augmented reality (AR) applications in STEM education illuminate pivotal insights and emerging trends that underscore the transformative potential of AR technology in educational settings:

1. *Applications of AR Across STEM Disciplines*

AR technology is versatile and dynamic, making it ideal for use in many different STEM fields, such as biology, physics, chemistry, mathematics, and engineering. In all of these areas, AR technology has allowed the emergence of new learning experiences that could be absorbed into any kind of learning need or appropriate for any curriculum.

Biology: AR education has revolutionized a number of crucial teaching practices in biology. Augmented reality allows students, in real-time, to observe biological simulations of various anatomical structures as virtual dissections. AR-enriched applications give students the opportunity to learn with a 3D virtual specimen—a virtual dissection on an augmented reality platform. The interaction of a student with such a virtual specimen provides the ability to understand biological entities in 3D space while allowing the student never to have to manipulate a physical training specimen. Such a multi-sensory interaction with natural objects will not only improve a student's understanding of the concept but will also stimulate the student's emotions and appreciation for the issues that currently affect living things.

Physics: The advent of AR technology in the field of physics has enabled interactive experiments. It has become a kind of cooperative partnership between a practicum and a thought experiment—a simulator for the most abstract and impossible concepts. With AR-enabled physics simulations, students get a tangible and instinctive feel for how things work at a fundamental level. AR technology immerses students in dynamic, interactive environments, deepening their grasp of physical principles and encouraging inquiry-based learning.

Chemistry: An AR contextualization of chemistry courses helps users experience and replicate lab-based experiments and observe chemical reactions. And not only can AR-enabled apps act as a safe and convenient platform where children can learn by doing the science, but they can also help them see the structure of the molecules, register the elements as they combine or break up at a particular instant of time, and appreciate the myriad properties of compounds—e.g., using virtual labs as your own crucible. Such a perspective is less about learning and more about allowing the user to experience everything.

Mathematics. In mathematics, AR technology gives us a unique opportunity to represent abstract mathematical concepts intuitively and creatively without any obligation to write on paper. First, students can use AR-enhanced algebra expressions and calculus, 2D/3D geometric shapes, and reasoning to learn interactively. If traditional mathematical classes teach students to take notes (or photocopies) from a blackboard, integrating AR with mathematics classes will develop students' mathematical thinking and ability to solve problems. Second, AR will provide them with advanced mathematical modelling and visualization tools to help them investigate complex mathematical concepts interactively and dynamically. Whether it is calculus, statistics, data visualization, or simply other more complex mathematical domains, AR will enrich mathematical simulations to enable the student to play with them and solve problems, thereby developing intuition. AR will not only polish our diamond but, by demonstrating abstract mathematical concepts visually, it will enable us to have a complete and vivid view of them. It will also help us develop analytical thinking through problem-solving skills.

Engineering. In addition, AR technology in engineering has been used to build immersive design environments and prototyping tools that allow students to better understand and manipulate complex concepts. Everything from architectural drawing and structural analysis to mechanical engineering and robotics can be tested through AR-enhanced simulations, giving students hands-on experience with designing and testing engineering solutions in a virtual world. This develops not only their understanding of engineering principles but also their creativity, innovation, and collaborative problem-solving skills, which are essential for success in the field.

Geoscience and spatial analysis: AR technology can show geological formations, landscape features, and 3D graphics. Combining AR-enabled applications with geospatial datasets in a learning context can let students explore topographic maps and terrain models and investigate natural hazards such as earthquakes, volcanoes, and landslides. Educators can also select geospatial data and GIS technology to bring students into a landscape where they can see Earth's processes, landforms, and environmental changes and engage in spatial thinking – key skills for geoscience and environmental science jobs.

Renewable Energy and Sustainable Technology: AR technology allows students to gain a better understanding of renewable energy systems, sustainable technologies, and strategies for environmental preservation. For example, when studying renewable energy sources, students can use AR-enabled applications that enable them to visualize solar panels, wind turbines, and hydroelectric dams. The AR program could also be designed to determine the efficiency of these devices by simulating their performance under different environmental parameters. Additionally, AR technology encourages students to develop renewable energy installations as well as other sustainable design prototypes that would help them prepare for the energy challenges of the future and support sustainable development. In short, AR technology improves students' grasp of the interdisciplinary principles involved in engineering and environmental design by engaging them in real-life activities.

Biomedical Engineering and Medical Device Design: Biomedical Engineering and Medical Device Design: AR technology can be applied in biomedical engineering education in order to simulate medical procedures, anatomical structures, and biomedical devices in a virtual environment. The potential uses of AR-assisted applications for students include medical device design and the design of prototypes; virtualizing surgical procedures; and offering new insights into biomedical imaging technology. Educators who integrate the concepts of anatomy, physiology, and engineering into AR experiences can make it possible for students to learn from a tactile, innovative perspective. In this way, they are preparing students to be ready for careers in healthcare technology, medical device design, and biomedical research.

Computer Science and Programming Education: Augmented Reality creates an unprecedented opportunity for teaching computer science and programming, where you can create interactive programming environments and visual programming to code directly. For instance, an AR-enabled application can allow students to not only learn Python, Java, or C++ programming; but also to create augmented-reality applications or games. AR technology can also empower students' coding skills and their thinking in computing; not only does the hardware provide immediate feedback about the code, but also a visual output from inside programs that are running. In terms of creativity and innovation, this suggests that learners will be effective in creating software and coding if they use such tools—that is, students can understand abstract notions about what is possible with programming languages or code; for example, in their gaming design, educational software development, scientific modeling, and simulation through the use of AR.

Robotics and Automation: In education, AR can be utilized to incorporate robotics and automation in such a way that a robot's systems, control algorithm, and robot behaviors are virtualized and simulated in a virtual environment. Students can use AR-enabled applications to design a robotic assembly, program and operate a virtual robot in different scenarios, and simulate robotic operations. By combining the principles of mechanical engineering, electrical engineering, and computer science into an AR experience, educational practitioners have a way of providing hands-on learning in the domain of robotics and automation, as well as preparing students for careers in robotics engineering, mechatronics, and industrial automation.

AR can be integrated with robotics and automation in an educational context, such as by simulating the robot-making process, control algorithms, and robotic behaviours. By making use of AR-enabled applications, students can design robotic assemblies, program and operate virtual robots, and conduct operations under different scenarios. By combining the principles of mechanical engineering, electrical engineering, and computer science, educators have a feasible direction to provide students with realistic learning experiences on robotics and automation, as well as a bridge to prepare them for a future career in robotics engineering, mechatronics and industrial automation.

Medical education and healthcare AR is being used more and more in medical education and health care training to imitate surgery, anatomical structures, and patient care situations. Medical students are able to wield AR-based apps to try out surgical techniques, manipulate human anatomy in three dimensions, and enact medical procedures in virtual hospital locations. AR technology can provide realistic, immersive training experiences that help medical professionals develop clinical skills, enhance diagnostic abilities, and improve patient results. Furthermore, AR-based medical simulations allow for a safe and economical means of training that does not put lives at stake as traditional methods do.

Astronomy: In terms of astronomy and space exploration, AR technology integrates scientific research results with educational resources to give users a near-realistic feel in an otherwise virtual setting where they can even conduct experiments! AR technology makes it possible. The celestial sphere overhead is virtually enhanced in students' eyes. It is now easier than ever to see how planets are formed from gas clouds, with star formation also being made visible here, experts believe, for the first time anywhere. Using AR devices, students may also view a galaxy's birth or stars that died. AR technology gives them a fun way to learn science. In this way, AR technology will become an important tool in the future science education of today's high school students, if they can afford it. Things change too fast today.

Table 1: STEM Disciplines and AR Applications

Discipline	Description	Literature
Biology	AR enhances understanding with virtual dissections and anatomy simulations.	[1, 10, 16, 25, 26, 31, 32]
Physics	AR visualizes complex phenomena, encouraging inquiry-based learning.	[2, 10, 16, 20, 25, 33, 34]
Chemistry	AR simulates laboratory experiments, providing hands-on learning experiences.	[3, 16, 17, 26, 35, 36]
Mathematics	AR offers innovative solutions for visualizing abstract concepts.	[4, 16, 17, 25, 26, 37, 38]
Engineering	AR fosters creativity and collaborative problem-solving in design.	[5, 12, 13, 16, 17, 21, 25, 26, 39, 40]
Geoscience and Geospatial Analysis	AR visualizes geological formations, promoting spatial reasoning.	[6, 12, 17, 23]
Renewable energy & Sustainable technology	AR fosters interdisciplinary learning in renewable energy systems.	[7, 13, 23, 24, 36, 39]
Biomedical Engineering and Medical Devices	AR facilitates hands-on learning in medical procedures.	[8, 10, 19, 28, 20, 25, 26]
Computer Science & Programming	AR enhances computational thinking in coding languages.	[9, 16, 17, 20, 37, 38]
Robotics and Automation	AR provides hands-on learning by simulating robotic systems.	[10, 13, 16, 18, 20, 40]
Medical Education and Healthcare	AR enhances clinical skills through realistic surgical simulations.	[10, 11, 19, 26, 27]
Astronomy & Space Exploration	AR fosters collaborative scientific inquiry in virtual space exploration.	[12, 16, 17, 21, 22, 38]

2. *Challenges and limitations associated with the integration of AR in educational settings*

The study found that integrating AR technology into educational settings presents various challenges and limitations that need to be addressed for successful implementation. These include:

Technical Complexity

Developing and deploying AR applications involves crossing a landscape of technical complexities, and it takes a professional background in 3D modeling, programming languages such as Unity or Unreal Engine, and the design of user interfaces to create immersive AR content. Educators who are not experts in these specialist skills have found it difficult to cope with learning AR development tools and techniques. Moreover, AR is an ever-changing technology environment, and not everyone can keep up with all the evolving standards and emerging platforms, making development more complex.

Cost and resource constraints

Adopting AR technology means spending a lot of money on hardware, software, and human resources. Financing devices such as smartphones, tablets and AR headsets used as the primary interface for AR experiences can stretch the budgets of institutions, especially in poor or under-resourced educational environments. Moreover, producing custom AR content alone requires money for buying software development tools and licenses and hiring good developers or designers. These monetary considerations may discourage educational institutions from adopting AR for teaching purposes, meaning students and teachers can't use it as readily.

Infrastructure and connectivity issues

For AR application software to be transmitted smoothly, it is essential that the telecommunications network be robust and that the Internet be reliable. Unfortunately, some educational institutions, especially in African developing countries, have infrastructure problems such as outmoded network equipment, limited bandwidth, and unreliable Internet connections, which are especially acute in rural or remote regions. Inadequate network infrastructure can cause real-time rendering and buffering errors in the picture or even learning interruptions. In addition, differences in internet access conditions have their own problems when it comes to AR-enhanced learning opportunities, leading to severe disparities between students in geographically unequal locations and with varying socioeconomic levels.

Access and Equity Concerns

Disparities in socioeconomic status, location, and disparities are liable to exacerbate educational opportunity inequalities. If you come from a poor background, you might not have the means to purchase the necessary hardware, your internet may not be reliable enough, and you are not going to receive the technical support required to fully benefit from an augmented reality-rich environment. The digital divide may widen, and the disadvantages faced by poor students themselves will be further exacerbated if action is not taken to redress this imbalance. Providing loaner devices, setting up Wi-Fi hotspots in communities, and offering subsidies for internet access are ways to even the playing field for underprivileged students. Efforts to promote inclusive access must include measures such as R&D to offer cheap AR-compatible devices, creating community Wi-Fi hotspots, and providing subsidies for internet access. Otherwise, the result will be that some can enjoy the benefits of AR education while others cannot.

Curriculum integration and pedagogical alignment

Integrating AR into past curricula has led to the double-edged problem of finding compatible AR experiences in connection with learning goals and educational methods: Teachers must consider how AR apps can better complement (rather than just hinder or deceive) the current pedagogical practice. AR materials attached to a curriculum and a pedagogy must be about outcome rather than decoration. But this obstacle stands between teachers and AR as pedagogy since no curricular framework or resources tell them how, when and where to integrate AR into teaching particular subjects to particular age groups.

Teacher Training and professional development

Educators may need to gain the required skills and confidence to make full use of AR technology in their existing teaching practices. Equipping teachers with professional knowledge and competences to leverage AR capabilities to serve learning and teaching demands requires a combination of pre-service training and in-service professional development. A range of hands-on AR workshops, online courses and peer mentoring programmes can help teachers become familiar with AR tools, formulate their pedagogical approaches to and with AR, and have a chance for field practice with AR-enriched learning activities. Support from technology experts and instructional designers in the use of AR technology in the classroom can be crucial in fostering a culture of innovation among education staff, thus supporting the effective use of AR tools in the classroom.

Privacy and ethical considerations

Data collection, tracking, and profiling may cause privacy worries when the next AR applications appear. There is an urgent need for educators to ensure they comply with national privacy laws and regulations while also guarding students' personal information with the appropriate defenses. Prior to using this technology in educational settings, ethical issues like consent, being a good digital citizen, using the technology, and the like should also be considered so that there are ways promoting safe and ethical practices.

Table 2: Challenges associated with the integration of AR applications

Challenges	**Description**	**Literature**
Technical Complexity	AR development demands expertise in 3D modeling, programming, and UI design, posing challenges for educators.	[2, 7, 9, 13, 16, 20, 29, 35]
Cost and Resources	Institutions face financial hurdles in procuring AR hardware and software, hindering adoption.	[6, 9, 11, 15, 26, 34]
Infrastructure	Poor network infrastructure limits the smooth transmission of AR applications, exacerbating educational inequalities.	[12, 13, 16, 10, 36]
Access and Equity	Socioeconomic and geographical disparities impede access to AR technology, widening educational gaps.	[5, 12, 15, 20, 25, 38]
Curriculum Integration	Aligning AR with learning objectives poses challenges due to the lack of tailored resources.	[4, 10, 16, 17, 25, 26, 36]
Teacher Training	Educators require comprehensive training to effectively integrate AR into teaching practices.	[11, 14, 16, 17, 20, 25, 26, 33]
Privacy and Ethics	Data privacy and ethical concerns arise from AR applications, necessitating compliance with regulations.	[5, 8, 11, 18, 19, 40]

3. *The potential of AR to address the diverse needs and preferences of learners in STEM education*

The future of AR technology is very promising. There is no doubt that it has huge potential in the field of education, especially for students who majored in science and technology subjects. AR will be beneficial for different types of learners, including their learning styles, levels of ability and the preferences for education. As a result, that might increase the motivation for learners with different various backgrounds to learn effectively.

Multimodal Learning Experiences: Incorporating various multimedia elements, such as 3D models, animations, videos, and audio, into educational materials is how AR technology revolutionizes the learning experience. For example, in a biology class, students can use AR-enabled apps to view a virtual human body model and rotate it in three dimensions to see different body systems. This visual and interactive approach caters to those learners who like to see everything in pictures. Similarly, auditory learners may also benefit from AR apps that include both visual and audio content. In a physics lesson about electromagnetism, for example, students can listen to audio explanations while they interact with virtual simulations of magnetic fields. AR gives you a variety of new ways to understand and interact with content, so there are more types of information one can use in different conditions.

Personalized Learning Paths: In addition to tracking students' needs, preferences, and proficiency levels, adaptive learning in AR can also adjust to provide an entirely personalized experience, including not only the best possible learning path but also a lesson—integrating literacy and mathematics in the same model; geography in one activity; and math exercises in the other. Another example: In a mathematical learning app, students do adaptable assessments that vary the difficulty level according to their performances, so as to always present them with an appropriate level of challenge. Additionally, AR apps will provide learners with personalized feedback and well-sequenced guidance that caters both to the individual's personal needs and expectations. For instance. If a student has difficulty grasping ideas on paper or in class, then this one-on-one computer helper could, in real-time, offer not only the necessary explanation of terms but also examples of differentiated exercises. Giving people more personalized learning experiences, AR allows them to take full responsibility for their learning process and speed of progress, so that motivation will improve in the end because they are more involved with what they are doing.

Inclusive Design and Accessibility Features: AR developers have to put inclusivity and accessibility first to accommodate learners with a diverse range of needs and disabilities. For example, AR apps could feature text-to-speech functionality so that the visually impaired may listen to audio narration of written texts. Along with adjustable font sizes, color contrast settings, and alternative input methods, these allow those with visual, auditory, motor, or cognitive impairments to interact effectively with AR content. What's more, AR apps could provide language support, translations, and subtitles that would make learners of different linguistic and cultural backgrounds comfortable. For instance, in a vocabulary acquisition program, students can opt to receive instructions and content in their chosen language. This makes the learning process even more accessible and inclusive.

Collaborative and Social Learning Environments: AR technology can promote collaborative and social learning experiences, encouraging learners to interact with each other or with virtual avatars in shared virtual spaces. Such activities as groups doing things together in AR, for example, project completion problems and solving problems in the environment, collaborative simulations, and other similar types of work promote teamwork, communication skills, and peer learning skills. By working in a supportive, interactive environment, one can do complex projects together, share ideas, and explore concepts. In addition, AR can enable remote collaboration and distance learning opportunities. It transcends geographical barriers to connect learners globally. AR makes live experiences more interactive and immersive, whether it be by promoting social interaction or enabling collaboration. A sense of belonging and community are fostered among learners through AR, which promotes collaboration in some of its applications.

Real-World Contextualization and Authentic Learning Experiences: The combination of AR technology and learning helps to bring basic concepts, such as abstract formulas or scientific laws, out into reality instead of leaving them just on the page. In doing this, learning becomes much more real, much more meaningful, and indeed memorable. Augmented reality (AR) applications that project digital information over physical objects and environments are now capable of transforming learning environments into immersive and authentic experiences.

These environments simulate real-world scenarios and contexts with the ability to overlay digital data on top real-life items, which provides the appearance of an even more authentic setting for events such as this. For example, augmented reality enables learners to visit historical sites, examine geological formations, and perform virtual experiments in their own homes. To this end, things are made easier or possible altogether by learning while doing without leaving the comfort of an armchair. The contextual nature of learning leads to even deeper insight and provides more significant material for critical thinking as well. It is interaction with practical context that realizes technical theories. By bridging the gap between theory and practice, AR prepares learners for real-world challenges and professional environments in STEM fields.

Table 3: Potential of AR to address the diverse needs and preferences of learners in STEM education

Potential Feature	Description	Literature
Multimodal Learning	Integrates multimedia for visual and auditory learners.	[8, 11, 14, 19, 25, 26, 38]
Personalized Paths	Adjusts to student needs, offers tailored learning.	[11, 16, 17, 20, 25, 26, 34]
Inclusive Design	Prioritizes accessibility with text-to-speech, multilingual support.	[7, 13, 14, 20, 26, 37]
Collaborative Environments	Fosters teamwork, social interaction in shared spaces.	[8, 14, 17, 21, 36]
Real-World Context	Contextualizes learning in immersive experiences.	[6, 12, 14, 19, 20, 35]

V. DISCUSSION

The study reveals hurdles and shortcomings inherent in achieving AR technology success in STEM education, however it should not underrate the transformative power of education using AR technology. One of the challenges described carries a message, albeit unintentionally, that the programming of an AR app is very complicated. But the same is true for creating 3D models, programming languages and user interface design for highly engaging AR content. Facing the steep learning curve that teachers lacking this expertise must tackle to become successful designers of immersive AR content is another obvious issue. A practical solution here involves joint learning and newfound understanding of using these new tools and trends among schools and companies that are sharing these goals. In this way, both tools and know-how, as well as methodologies and best practices, can be shared between schools and companies. Undoubtedly, such genuinely high-quality education in AR technology will be achieved at the undergraduate level.

A serious financial hurdle to widespread deployment is that implementing AR in education is a significant financial undertaking to procure the hardware and software licenses, in addition to the personnel required. This is a financial burden that a lot of education can't afford especially cash-strapped schools. There are ways in which open-source resources can be used in lieu of financial outlay, grant acquisitions and creative work with technology companies can all help ease the financial stress of AR deployment, and further democratize access to AR technology teachers and students alike.

Equity and inclusion raise questions about the role and deployment of AR in education too. Educational opportunities can become even more unequal if students have different access to technology and other resources. Students from the marginalized sections of a community are likely to be more affected than others. Overcoming these inequality boundaries through activities such as addressing infrastructure issues, providing support to teachers operating in underprivileged settings, and offering financial aid and skills, will help achieve a fair system. This will also allow for equitable access, with every student getting to use AR-supported learning experiences. More importantly, using universal design principles in the creation of AR applications can make them accessible to a greater community of needs and learner varieties, and build a more inclusive learning environment.

Although AR presents considerable challenges for those educators tasked with adapting it to STEM education, let us insist that it could potentially change pedagogical practices and learning outcomes altogether. AR allows students to engage in these new kinds of interactions that, besides enhancing their understanding of complex ideas, could also develop their critical thinking and problem-solving skills, and strengthen their disciplinary knowledge.

The fact that, with AR, students can be more fully and actively engaged in the process of learning is one of its key benefits. In AR, it is as if learning is happening in the real world: because digital information is overlaid on the physical world, learning is experienced in a real, live situation. By superimposing virtual elements of the world, AR provides an environment where learning is experiential, active and deep. More than just receiving information, seeing and interacting with the virtual item can capture the student’s interest and engagement. Thus, the deeper the engagement, the deeper the understanding, and the greater likelihood of information being better embedded.

Furthermore, framing AR in conversations around curriculum design and evaluation also affords teachers the opportunity to shift learning modalities to become participatory, student-centered learning spaces that cater to students’ unique learning styles and personal tastes. AR applications can be tailored to divergent learning modalities. This allows the student to take ownership of the content from different angles and in the ways that are best suited, be it visualized, simulated or interactive. As a tool, AR provides teachers with a comprehensive ‘toolbox’ with which they can design personalized learning spaces that cater to every student.

In addition, AR allows such concepts to be related and situated in a real-world context, giving the learning process more relevance, meaning and interest. With the use of AR, information can be revealed on top of objects and the environment to help bridge the gap between theory and practice. Students can observe how concepts work in the real world, with the aid of their phones. Aside from aiding students to understand abstract ideas, such contextualization might fuel their passion in the sciences because they realize the significance and usefulness of the subjects in their daily lives.

VI. CONCLUSION

STEM offers a new frontier with the use of AR technology offering new ways on how STEM can be taught. With STEM education facing a number of challenges through technical complexity, economic competitiveness and achievement, as well as equitable service to students, AR technologies has the potential to increase students' levels of engagement and motivation. For learners who possess unique learning styles and preferences, AR provides the opportunity to create an immersive and interactive learning environment that can be easily differentiated for a student and facilitate the development of critical thinking, problem-solving and disciplinary knowledge.

This study has one limitation as it relies on existing literature and empirical research. AR's advancements and new research continue to emerge, and there are perhaps even more insights and developments than captured in this review. Furthermore, the editorial standards set by both English-language publications and peer-reviewed sources emphasize a critical bias. It may be that valuable contributions from non-English sources or alternative publication formats are overlooked.

There are a number of possible pathways for research and further development in the field of AR-aided education. Further research is urgently needed to determine whether AR programs are effective in different STEM fields and across different grades. Through research, we can find ways to determine the exact impact of AR on student learning outcomes, their attitudes toward STEM subjects, and their long-term retention of knowledge. What's more, designing user-friendly AR authoring tools and platforms that give educators the capability to do these things without having to know anything about programming is something that is being called for. We need continued research on user-friendly AR authoring tools and platforms that enable educators without special technical skills to create and deploy AR content.

In addition, educational research in the future should consider whether AR integration in education raises issues of fairness. It's crucial that we address these issues to ensure that AR technology is accessible to all. Moreover, affordable home-grown IP addresses, local cell phone networks, and the use of low-cost headsets has the potential to foster greater regional penetration of AR technology. We need to bridge the digital divide and commit ourselves to equalizing opportunities for AR-supported pedagogy in science, technology, engineering, and mathematics.

References

[1] Xiong, J., Hsiang, E. L., He, Z., Zhan, T., & Wu, S. T. (2021), “Augmented reality and virtual reality displays: emerging

technologies and future perspectives” in *Light: Science & Applications*, 10(1), 216.

[2] Makhataeva, Z., & Varol, H. A. (2020), “Augmented reality for robotics: A review”, *Robotics*, 9(2), 21.

[3] Garzón, J. (2021), “An overview of twenty-five years of augmented reality in education”, in *Multimodal Technologies and Interaction*, 5(7), 37.

[4] Osadchyi, V. V., Valko, N. V., & Kuzmich, L. V. (2021), “Using augmented reality technologies for STEM education organization”, In *Journal of Physics: Conference Series* (Vol. 1840, No. 1, p. 012027). IOP Publishing.

[5] Tytler, R. (2020), “STEM education for the twenty-first century. In J. Anderson & Y. Li (Eds.)”, in *Integrated approaches to STEM education (pp. 21–43)*. Springer.

[6] Tandrayen-Ragoobur, V., & Gokulsing, D. (2021), “Gender gap in STEM education and career choices: what matters?” in *Journal of Applied Research in Higher Education*, 14(3), 1021-1040.

[7] Suhirman, S., & Prayogi, S. (2023), “Overcoming challenges in STEM education: A literature review that leads to effective pedagogy in STEM learning”, in *Jurnal Penelitian Pendidikan IPA*, 9(8), 432-443.

[8] Yu, J., Denham, A. R., & Searight, E. (2022), “A systematic review of augmented reality game-based Learning in STEM education”, *in educational technology research and development*, 70(4), 1169-1194.

[9] Criollo-C, S., Abad-Vásquez, D., Martic-Nieto, M., Velásquez-G, F. A., Pérez-Medina, J. L., & Luján-Mora, S. (2021), “Towards a new learning experience through a mobile application with augmented reality in engineering education” in *Applied Sciences*, 11(11), 4921.

[10] Erbas, C., & Demirer, V. (2019), “The effects of augmented reality on students' academic achievement and motivation in a biology course”, in *Journal of Computer Assisted Learning*, 35(3), 450-458.

[11] Tang, K. S., Cheng, D. L., Mi, E., & Greenberg, P. B. (2020), “Augmented reality in medical education: A systematic review”, *in Canadian medical education journal*, 11(1), e81.

[12] Xu, J., & Moreu, F. (2021), “A review of augmented reality applications in civil infrastructure during the 4th industrial revolution”, in *Frontiers in Built Environment*, 7, 640732.

[13] Dursun, M. (2020, April), “An Augmented Reality Based Modular Platform for Solar Energy Education”, In *Proceedings of the 2020 6th International Conference on Computer and Technology Applications* (pp. 149-153).

[14] Sereno, M., Wang, X., Besançon, L., Mcguffin, M. J., & Isenberg, T. (2020), “Collaborative work in augmented reality: A survey” in *IEEE Transactions on Visualization and Computer Graphics*, 28(6), 2530-2549.

[15] Yoon, S., & Oh, J. (2022), “A theory-based approach to the usability of augmented reality technology: A cost-benefit perspective”, in *Technology in Society*, 68, 101860.

[16] Macariu, C., Iftene, A., & Gîfu, D. (2020), “Learn chemistry with augmented reality” in *Procedia Computer Science*, 176, 2133-2142.

[17] Oleksiuk, V., & Oleksiuk, O. (2020), “Exploring the potential of augmented reality for teaching school computer science”, In Proceedings of the 3rd *International Workshop on Augmented Reality in Education (No. 2731). CEUR Workshop Proceedings.*

[18] Iqbal, M. Z., Xu, X., Nallur, V., Scanlon, M., & Campbell, A. G. (2023), “Security, ethics and privacy issues in the remote extended reality for education”, In *Mixed Reality for Education* (pp. 355-380). Singapore: Springer Nature Singapore.

[19] Neely, E. L. (2019), “Augmented reality, augmented ethics: who has the right to augment a particular physical space?”, in *Ethics and Information Technology*, 21(1), 11-18.

[20] Radu, I., Joy, T., Bowman, Y., Bott, I., & Schneider, B. (2021), in “A survey of needs and features for augmented reality collaborations in collocated spaces” in *Proceedings of the ACM on Human-Computer Interaction*, 5(CSCW1), 1-21.

[21] Herfana, P., Nasir, M., & Prastowo, R. (2019), “Augmented reality applied in astronomy Subject” in *Journal of Physics: Conference Series* (Vol. 1351, No. 1, p. 012058). IOP Publishing.

[22] Önal, N. T., & Önal, N. (2021), “The effect of augmented reality on the astronomy achievement and interest level of gifted students” *in Education and Information Technologies*, 26(4), 4573-4599.

[23] Badilla-Quintana, M. G., Sepulveda-Valenzuela, E., & Salazar Arias, M. (2020), “Augmented reality as a sustainable technology to improve academic achievement in students with and without special educational needs” in *Sustainability*, 12(19), 8116.

[24] Sun, Q., Hsiao, I. H., & Chien, S. Y. (2023), “Immersive educational technology for waste management learning: A study of waste detection and feedback delivery in augmented reality” in *In International Conference on Human-Computer Interaction* (pp. 509-515). Cham: Springer Nature Switzerland.

[25] Fominykh, M., Wild, F., Klamma, R., Billinghurst, M., Costiner, L. S., Karsakov, A., ... & Smolic, A. (2020), “Model augmented reality curriculum” In *Proceedings of the Working Group Reports on Innovation and Technology in Computer Science Education* (pp. 131-149).

[26] Mohamed, T. I., & Sicklinger, A. (2022), “An integrated curriculum of virtual/augmented reality for multiple design students”, *Education and Information Technologies*, 27(8), 11137-11159.

[27] Gerup, J., Soerensen, C. B., & Dieckmann, P. (2020), “Augmented reality and mixed reality for healthcare education beyond surgery: an integrative review” in *International journal of medical education*, 11, 1.

[28] Viglialoro, R. M., Condino, S., Turini, G., Carbone, M., Ferrari, V., & Gesi, M. (2021) in “Augmented reality, mixed reality, and hybrid approach in healthcare simulation: a systematic review”, in *Applied Sciences*, 11(5), 2338.

[29] Stemler, S. E. (2015), “Content analysis. Emerging trends in the social and behavioral sciences”, in *An Interdisciplinary, Searchable, and Linkable Resource*, 1-14.

[30] Ishengoma, F., Mselle, L., & Mongi, H. (2019), “Critical success factors for m-Government framework” in *The Electronic Journal of Information Systems in Developing Countries*, 85(1), e12064.

[31] El Kouzi, M., Mao, A., & Zambrano, D. (2019), “An educational augmented reality application for elementary school students focusing on the human skeletal system”, In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)* (pp. 1594-1599). IEEE.

[32] Sun, Y., Yuan, T., Wang, Y., Sun, Q., Hou, Z., & Du, J. (2024), “Augmented reality presentation system of skeleton image based on biomedical features” In *Virtual Reality*, 28(2), 98.

[33] Bennour, S., Ulrich, B., Legrand, T., Jolles, B. M., & Favre, J. (2018). “A gait retraining system using augmented-reality to modify footprint parameters: Effects on lower-limb sagittal-plane kinematics” in *Journal of biomechanics*, 66, 26-35.

[34] Bakri, F., Kusuma, R., & Permana, A. H. (2021), “TPACK and augmented reality in kinematics practicum module: forming hots physics education students”, *in Journal of Physics: Conference Series* (Vol. 2019, No. 1, p. 012041). IOP Publishing.

[35] Elford, D., Lancaster, S. J., & Jones, G. A. (2023), “Augmented reality and worked examples: Targeting organic chemistry competence” in *Computers & Education: X Reality*, 2, 100021.

[36] Yamtinah, S., VH, E. S., Saputro, S., Ariani, S. R. D., Shidiq, A. S., Sari, D. R., & Ilyasa, D. G. (2023), “Augmented reality learning media based on tetrahedral chemical representation: How effective in learning process?”, *Eurasia Journal of Mathematics, Science and Technology Education*, 19(8), em2313.

[37] Rossano, V., Lanzilotti, R., Cazzolla, A., & Roselli, T. (2020), “Augmented reality to support geometry learning” in *IEEE Access*, 8, 107772-107780.

[38] Widada, W., Herawaty, D., Nugroho, K. U. Z., & Anggoro, A. F. D. (2021), “Augmented Reality assisted by GeoGebra 3-D for geometry learning” *in Journal of Physics: Conference Series* (Vol. 1731, No. 1, p. 012034). IOP Publishing.

[39] Scaravetti, D., & François, R. (2021), “Implementation of augmented reality in a mechanical engineering training context” in *Computers*, 10(12), 163.

[40] Singh, S., & Student, B. T. F. Y. (2016), “An overview of augmented reality in various fields of Mechanical Engineering”, *International Journal of Applied Research in Science and Engineering*, 163-168.

Fredrick Ishengoma is a Senior Lecturer at the Department of Information Systems and Technology (IST), College of Informatics, the University of Dodoma, Tanzania. He holds a PhD of Information Systems from the University of Dodoma, Tanzania, a master’s degree in computer and information engineering (CIE) from Daegu University, South Korea, and a bachelor’s degree in information and communication technology management (ICTM) from Mzumbe University, Tanzania. His research interests include ICT for Development (ICT4D), e-Government, Government, and social dimensions of ICT. Email: ishengomaf@gmail.com

Lucian Ngeze has been a lecturer and researcher at the University of Dodoma (UDOM) since 2010. He completed his Ph.D. in Educational Technology from the Indian Institute of Technology Bombay. His research focuses on training schoolteachers on effectively integration of ICT tools in teaching and learning. He has developed a model that can be used to conduct effective cascaded schoolteacher training workshops on ICT integration in Tanzania. His other areas of research interest include teacher professional development, e-learning, Instructional Design, Online Courses, and MOOC Design. Dr. Ngeze has trained teachers in face-to-face workshops and online modes via Online Courses and Massive Open Online Courses (MOOCs). Lucian has also developed 5 online courses that aimed at helping teachers use innovative teaching strategies of the 21st –century to transform their teaching practices. He has researched the effective use of technology in teaching and learning in secondary schools in Tanzania. He has published papers in international journals in the field and presented in various conferences. He has also been one of the National facilitators in the National ICT Programme for Secondary School Teachers in Tanzania. Email: lucianngeze@yahoo.com

Placidius Ndibalema is a senior Lecturer of Digital media psychology and ICT Pedagogical Development at UDOM. He has been engaged fully in four projects at different positions. The Co-PI in the project funded by the Government of Tanzania and GPE LANES and the second research project about Tanzania Early Grade Social and Emotional Skills and Phonics-Based Literacy Learning Agenda funded by USAID. He has been working as the Principal Investigator in other two projects funded by SPIDER-Stockholm University. His PhD focused on Transforming Teacher's professional Competence in the use of ICT as a Pedagogical Tool which engaged teachers in online community of learning. He has researched and published widely in digital media psychology and early childhood learning through technology. Dr Ndibalema, is an expert in ICT pedagogical development and scientific inquiry and digital media psychology competencies in particular. He is highly experienced in design-based research methodologies, and in project implementation and evaluation using mixed-methods. He has researched widely in the area of basic education, secondary education and technological literacy among youth, out-of-school children and youth, the pastoralist minority and higher education. He has experience in bibliometric analysis (Meta-analysis) using VOS Viewer software and qualitative content as well as relational analysis, data visualization network mapping using Atlas.ti software. Email: placidius.ndibalema@gmail.com