Chapter 6

STEM, Metaverse and Augmented Reality

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Chapter Highlights

The following points outline the core dimensions, opportunities, and challenges of integrating immersive technologies into STEM education, with a particular emphasis on pedagogical innovation, learning outcomes, assessment and learning analytics, and future-oriented instructional models. Together, they highlight the transformative potential of immersive technologies while underscoring the need for thoughtful, ethical, and sustainable implementation in STEM teaching and learning.

- Key Components of STEM Education – Integration of science, technology, engineering, and mathematics in teaching and learning.
- Role of Immersive Technologies – Impact of Augmented Reality, Virtual Reality, Metaverse applications on STEM education.
- Pedagogical Impacts and Learning Outcomes – Student interaction, collaboration, active learning, and development of scientific process skills.
- Assessment and Learning Analytics – Personalized feedback, learning analytics, and innovative assessment methods.
- Challenges and Limitations – Technical infrastructure, costs, privacy, and teacher training obstacles.
- Future Directions – Adaptive learning models, AI integration, inclusive policies, and interdisciplinary applications.

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Introduction

STEM (Science, Technology, Engineering, and Mathematics) education embodies a cohesive, interdisciplinary methodology aimed at providing students with the requisite knowledge and skills to tackle intricate global issues of the 21st century, including climate change and resource depletion (Marzuki et al., 2024). STEM education combines science, technology, engineering, and math to help students see the whole picture and become creative, imaginative problem-solvers.

The complexity of contemporary global issues requires students to move beyond rote memorization and disciplinary silos, embracing an educational paradigm that promotes critical, logical, and systematic thinking (Kelley & Knowles, 2016; Smith et al., 2022). This interdisciplinary approach helps students connect STEM subjects in relevant ways, which improves their problem-solving skills and knowledge of concepts (Thibaut et al., 2018).

Recent advances in educational technologies have strengthened STEM education by providing interactive, immersive, and student-centered learning experiences (Petrov & Atanasova, 2020). Among these, Metaverse and Augmented Reality (AR) technologies have garnered attention for their potential to transform traditional classrooms into highly engaging environments. Augmented Reality overlays digital content onto real-world contexts to support conceptual visualization, while the Metaverse provides collaborative virtual spaces where students can interact, problem-solve, and engage authentically beyond physical limitations (Tene et al., 2024).

These immersive technologies foster active learning, collaboration, and critical thinking, improving student engagement, knowledge retention, and performance across STEM disciplines (AlGerafi et al., 2023). In engineering education, AR enhances visualization and problem-solving skills critical for addressing societal challenges (Suhail et al., 2024). Also, AR and Metaverse apps help people learn 21st-century skills like creativity, innovation, communication, digital literacy, and teamwork. They also help people understand complex ideas better by giving them more opportunities to work together (Akçayır & Akçayır, 2017).

This chapter examines the intersection of STEM, Metaverse, AR, with an emphasis on theoretical foundations, practical applications, pedagogical impacts, and emerging challenges. By systematically reviewing current research, it highlights effective educational practices and provides insights into future directions for integrating immersive technologies into STEM curricula.

Emerging Technologies in STEM Education: A Theoretical Framework

STEM education is inherently interdisciplinary, combining scientific inquiry, technological innovation, engineering design, and mathematical reasoning into holistic learning experiences. This interdisciplinary nature aligns closely with the demands of the 21st century, where problem-solving often requires knowledge and skills across multiple domains (Marzuki et al., 2024). The incorporation of emerging technologies into STEM significantly enhances this potential by offering novel opportunities for visualization, simulation, and experimentation. These technologies allow students to participate in genuine, real-world problem-solving situations that require the simultaneous application of knowledge from various disciplines (Smith et al., 2022). Technologies such as VR, AI, AR exemplify this by facilitating experiential learning and fostering interdisciplinary approaches to complex problems (Chiu & Li, 2023). Moreover, integrating STEM content through inquiry-based and design-based learning enhances students' skills across diverse STEM disciplines and promotes a profoundly interdisciplinary learning environment. Despite this potential, a lack of synthesized frameworks has hindered the establishment of a robust theoretical foundation for STEM education (Aguilera et al., 2021).

The TPACK framework, which is based on Shulman's Pedagogical Content Knowledge, is a solid theoretical tool for looking at the complicated relationship between technology, pedagogy, and content that is needed for good teaching (Li & Li, 2024). This framework emphasizes that successful technology integration arises from the synergistic interplay of technological knowledge, pedagogical strategies, and subject-specific content, moving beyond simplistic views of technology as merely an additive tool (Jimoyiannis, 2010). Early research primarily established TPACK's theoretical underpinnings, while recent studies have solidified its utility in STEM education, particularly in supporting teacher adaptability, blended learning, and professional development (Irwanto, 2021). Within STEM contexts, TPACK highlights the necessity for educators to master content and pedagogy while also developing competencies in using advanced technologies such as AR and Metaverse platforms.

From a digital transformation perspective, STEM education is increasingly shaped by global policy frameworks, such as OECD's Learning Compass 2030 and UNESCO's guidelines on digital literacy. These frameworks emphasize not only the integration of emerging technologies but also the cultivation of adaptable, future-ready learners, thereby influencing curriculum development and pedagogical practices in higher education (Lyngdorf et al., 2024). They support transformative learning opportunities that cultivate 21st-century skills such as creativity, critical thinking, collaboration, and problem-solving, which are crucial for tackling global societal issues like climate change and significant human migrations (Rusmin et al., 2024). Furthermore, these directives promote the incorporation of value-based competencies alongside academic and technical skills, fostering sustainability, ethical awareness, and digital literacy (Cañavate et al., 2025).

This paradigm shift leverages technologies such as AR, VR, and Mixed Reality to create dynamic, interactive learning experiences within STEM disciplines. AR, for instance, overlays digital content onto real-world contexts to enhance conceptual visualization, while the Metaverse offers immersive, multi-user environments where students can collaborate, engage in problem-solving, and experience authentic scenarios (Tene et al., 2024). Combining these technologies helps people understand difficult ideas better, makes them more motivated, makes group learning more fun, and helps them learn how to be ethical and value-based. Empirical research illustrate their teaching efficacy, including enhancements in student engagement, knowledge retention, and performance across STEM fields (Shirazi & Behzadan, 2015). Moreover, systematic reviews that follow PRISMA principles and PICOS frameworks not only show how immersive technologies can improve learning outcomes, but they also stress how these technologies can help connect policy directions with what happens in the classroom (Tene et al., 2024).

The Concept of Metaverse and Its Applications in STEM Education

The Metaverse, which Neal Stephenson first thought about in his 1992 book, has gone from being a literary vision to an actual technological goal thanks to improvements in virtual reality (VR), augmented reality (AR), and blockchain technology (Chen et al., 2024). This “post-reality cosmos” merges physical and digital realms into a persistent, multi-user environment, offering a continuous and enduring virtual experience. Users interact through avatars and co-create experiences analogous to real-world social activities, fostering a participatory and engaging digital ecosystem (Almeman et al., 2025).

The Metaverse is a network of real-time 3D virtual worlds that are all connected. It lets people communicate with each other in a wide range of ways and have digital identities that last forever. By integrating virtual, augmented, and mixed realities, and enhancing experiences with haptic feedback and other sensory technologies, it allows users to interact with digital objects and each other in real-time, creating a profound sense of presence (Huynh-The et al., 2023). While definitions vary across disciplines, common conceptualizations emphasize a three-dimensional online environment where users represented by avatars engage in social, economic, and educational activities within a persistent, immersive digital realm (Dwivedi et al., 2022). This distinguishes the Metaverse from conventional VR systems and digital twins, which primarily focus on simulated interfaces or replication of real-world assets (Tu & Silva, 2025).

The incorporation of the Metaverse into STEM education signifies a substantial educational advancement (Lin et al., 2022). Leveraging VR, AR, and 3D technologies, it facilitates a transition from traditional classrooms to dynamic, immersive virtual environments (Almeman et al., 2025). Students can conduct experiments in virtual laboratories, explore engineering designs in 3D, simulate mathematical models dynamically, and engage in collaborative project-based learning without the limitations of safety, logistics, or physical infrastructure (Zhang et al., 2022). These immersive experiences encourage active engagement, higher-order thinking skills like analysis, synthesis, and assessment, and a better grasp of difficult STEM concepts.

Beyond practical simulations, the Metaverse supports personalized learning pathways and adaptive assessments tailored to individual student needs, moving past standardized testing (Onu et al., 2023). It also enhances social learning by enabling interaction with peers and instructors in shared virtual spaces, which is critical for teamwork-based problem-solving in STEM fields (Chen et al., 2024). Immersive technologies integrated onto these platforms have regularly demonstrated enhancements in student engagement, motivation, creativity, and skill learning (Tene et al., 2024).

Moreover, the Metaverse bridges the gap between digital policy frameworks and classroom practice, facilitating alignment with global educational goals such as digital literacy, accessibility, and 21st-century competency development (Dahan et al., 2022). By combining physical and virtual realities in shared 3D environments, it moves beyond conventional e-learning systems to offer deeper immersion, interactivity, and real-world relevance, fostering a comprehensive, participatory, and adaptive STEM learning ecosystem (Almeman et al., 2025).

This combination of immersive technology not only solves the logistical and moral problems that traditional labs have, but it also offers scalable solutions for making sure that everyone has access to high-quality educational experiences. Students cultivate essential competencies in critical thinking, problem-solving, teamwork, and creativity required for 21st-century STEM careers through these immersive, interactive, and adaptable virtual environments (Onu et al., 2023). The Metaverse thus represents a transformative paradigm, converging technological innovation with pedagogical practice to redefine STEM education for contemporary and future learners (Chen et al., 2024).

STEM Learning Experiences through Augmented Reality (AR)

Augmented Reality (AR) is the use of mobile devices, wearable technology, or head-mounted displays to add digital material, including 3D objects, animations, or simulations, to real-world settings (Lastrucci et al., 2024; Sulak & Koklu, 2024). By overlaying virtual objects onto physical surroundings in real-time, AR enables learners to perceive, interact with, and manipulate digital information within authentic contexts (Sommerauer & Müller, 2014). Unlike Virtual Reality, which fully immerses users in synthetic worlds, AR enhances reality, providing a bridge between abstract concepts and tangible experiences. This affordance makes AR particularly suitable for education, as it facilitates experiential learning, conceptual visualization, and engagement with otherwise intangible or complex phenomena (Kim & Choi, 2025).

AR transforms traditional pedagogical approaches by providing interactive experiences that merge digital and physical learning environments (Chin et al., 2020). For instance, students can visualize molecular structures in chemistry, simulate astronomical models in physics, or manipulate 3D engineering designs, thereby enhancing both understanding and retention of STEM concepts (Ibáñez & Kloos, 2018; Mystakidis et al., 2021). By promoting active involvement, AR motivates learners to transition from passive knowledge absorption to experiential exploration, thereby cultivating higher-order cognitive skills including analysis, synthesis, and assessment (Palada et al., 2024).

Recent improvements in mobile technology, such as high-resolution cameras, advanced sensors, and wearable devices, have made AR available to everyone allowing it to move beyond specialized laboratory contexts into everyday classrooms (Marín et al., 2023). AR applications can support collaborative learning, enabling groups of students to jointly manipulate digital objects and engage in problem-solving activities (Lunding et al, 2023). Furthermore, gamified AR experiences and tangible interfaces increase motivation, curiosity, and engagement, particularly in younger learners or abstract disciplines like chemistry (Tene et al., 2024).

The integration of AR into STEM education also addresses the challenges of remote and resource-limited learning environments. Virtual laboratories, enabled through AR, allow safe experimentation and repeated practice without the constraints of physical materials or risk (Iqbal & Campbell, 2022). Such platforms support constructivist learning by permitting learners to test hypotheses, observe outcomes, and iteratively refine their understanding in a controlled, interactive environment. These experiences cultivate metacognitive skills, expert thinking, and decision-making capabilities essential for professional development in scientific and engineering disciplines (Kalemkuş & Kalemkuş, 2024).

In addition, AR fosters spatial reasoning and visualization skills, critical for STEM disciplines where manipulating 3D structures and understanding abstract relationships are essential (Akçayır & Akçayır, 2016). Augmented reality (AR) lets learners directly interact with complicated systems by putting digital models on top of real-world situations. This closes the gap between theory and practice (Özçakır & Çakıroğlu, 2021). This immersive capability encourages active participation, lessens cognitive load, and improves accessibility, which supports different ways of learning and encourages inclusive teaching methods (Lampropoulos et al., 2022).

Empirical evidence demonstrates that AR-based STEM learning improves student motivation, engagement, and performance across multiple disciplines. For example, AR applications in engineering enhance collaborative problem-solving, enable exploration of intricate machine designs, and facilitate the comprehension of complex scientific phenomena (Suhail et al., 2024). In chemistry and biology, AR simulations allow learners to conduct experiments, manipulate molecular models, and explore anatomical structures safely, providing repeated and scaffolded practice that strengthens both conceptual and procedural knowledge (Mansour et al., 2024).

Moreover, AR supports teacher professional development by offering immersive platforms for training and curriculum experimentation, enabling educators to refine instructional strategies, integrate interactive content, and enhance student engagement (Suhail et al., 2024). The blend of interactive visualizations, chances to work together, and gamified experiences makes AR a powerful tool for teaching 21st-century skills including critical thinking, problem-solving, creativity, and teamwork (Petrov & Atanasova, 2020).

In summary, the integration of Augmented Reality technologies in STEM education represents a paradigm shift in teaching and learning. AR combines real and virtual worlds to provide immersive, interactive, and personalized learning experiences that improve understanding of concepts, increase engagement, and develop important cognitive and metacognitive skills. Through safe experimentation, collaborative problem-solving, and dynamic visualization, AR empowers learners to engage deeply with complex STEM concepts, laying the foundation for both academic achievement and professional competence in the 21st century (AlGerafi et al., 2023).

Pedagogical Impacts and Learning Outcomes

Tene et al. (2024) say that immersive technologies, like Augmented Reality (AR), Virtual Reality (VR), and mixed reality, have changed STEM education over time by making it more engaging, collaborative, and hands-on. These technologies allow learners to engage with abstract and complex concepts in ways that transcend traditional classroom limitations, enhancing comprehension, engagement, and skill acquisition. For instance, augmented reality (AR) adds digital information to the real world, allowing students to work with 3D models and see how complicated processes work. Virtual reality (VR) and Metaverse platforms, on the other hand, provide fully immersive spaces for trying things out and solving problems (AlGerafi et al., 2023).

One of the most important effects of modern technologies on teaching is that they encourage students to work together and talk to each other. AR applications facilitate group exploration of digital objects, whereas Metaverse environments provide shared virtual spaces for collaborative project design, discussion, and reflection (Tene et al., 2024). This interaction supports the development of teamwork, communication, and social learning skills, essential competencies for modern STEM education. Evidence indicates that immersive technology can substantially improve collaborative problem-solving by enabling learners to model real-world situations and share ideas in ways that are challenging to replicate in conventional classrooms (Mansour et al., 2024).

In addition to collaboration, immersive technologies foster active learning and student engagement. By integrating simulations, gamified tasks, and interactive modules, students move from passive knowledge reception to active participation, which promotes critical thinking and knowledge retention (AlGerafi et al., 2023; Bermejo et al., 2023). Studies indicate that AR and VR reduce cognitive load, making abstract scientific and mathematical concepts more accessible, while simultaneously increasing learner motivation and imaginative capabilities (Tene et al., 2024). For younger learners, AR-supported activities provide scaffolding and visualizations that facilitate comprehension and encourage the construction and revision of mental models (Koklu & Sulak, 2021).

The cultivation of scientific process skills and problem-solving abilities is an essential aspect of STEM education. Immersive technology allow students to do experiments that would be dangerous, expensive, or impossible to do in a regular lab (Tene et al., 2024). Virtual laboratories provide dynamic, secure, and interactive settings in which learners can change variables, employ measurement instruments, and monitor outcomes in real time (Abdelmoneim et al., 2022). This hands-on method promotes a constructivist learning framework, cultivating metacognitive skills, expert reasoning, and iterative problem-solving capabilities that emulate professional scientific investigation (Kalemkuş & Kalemkuş, 2024). Such experiences enhance students' ability to transfer knowledge, make informed decisions, and develop confidence in applying STEM concepts across disciplines.

Furthermore, immersive technologies facilitate assessment and learning analytics opportunities. Digital platforms embedded within AR, VR, and Metaverse environments can track student interactions, engagement patterns, and problem-solving strategies, enabling personalized feedback and adaptive learning (Suhail et al., 2024; Halim & Ismail, 2025). These analytics tools allow educators to move beyond traditional summative assessments by capturing a broader range of learning behaviors and outcomes, such as collaboration, decision-making, and experimental exploration (Suhail et al., 2024). By combining immersive experiences with learning analytics, instructors can tailor interventions, monitor skill development, and identify areas where students may require additional support.

Immersive technologies also support visualization and spatial reasoning, which are critical for STEM disciplines. The ability to manipulate 3D structures in virtual or augmented environments allows students to understand complex molecular, anatomical, or engineering systems more intuitively (Sviridova et al., 2023). For instance, AR applications enable learners to superimpose anatomical models onto physical space, facilitating exploration and comprehension of spatial relationships, while VR-based simulations replicate laboratory processes in a risk-free environment (Almeman et al., 2025). Such experiences contribute not only to cognitive gains but also to motivational and affective outcomes, as learners engage more fully with immersive content.

The incorporation of the Metaverse and AR into educational systems signifies a transformative transformation that facilitates contextualized, individualized, and cooperative learning experiences. These technologies can simulate real-world challenges, providing students with authentic problem-solving opportunities that strengthen STEM skills and cognitive flexibility (Thangavel, 2025). The immersive nature of these platforms also facilitates adaptive learning, allowing students with varying prior knowledge, learning styles, and skill levels to engage meaningfully with complex concepts (Poupard et al., 2025). Research underscores the importance of evaluating these technologies not only for engagement but also for long-term learning outcomes, emphasizing knowledge retention, skill transfer, and motivation as key indicators of success (Cao & Yu, 2023; Shankar, 2023).

Another notable pedagogical advantage is enhanced accessibility. Virtual laboratories and AR modules provide equitable learning opportunities for students in remote or underserved areas, ensuring continued access to high-quality STEM experiences (Ananikov, 2024). These platforms allow learners to experiment repeatedly, receive immediate feedback, and develop competence in areas where physical resources may be limited (Abdelmoneim et al., 2022). Additionally, immersive technologies encourage learner autonomy, self-confidence, and reflective practice, which are crucial for lifelong learning in STEM disciplines (Kalemkuş & Kalemkuş, 2024).

Research consistently demonstrates that immersive technologies improve academic performance. AR and VR interventions in STEM have shown positive effects on test scores, conceptual understanding, and applied skill development (Bermejo et al., 2023). Mixed reality and virtual simulations improve lab abilities, help people see scientific phenomena, and make people more interested in the material (Petrov & Atanasova, 2020). Moreover, these technologies foster creativity and innovation, allowing students to explore alternative solutions and construct knowledge in ways that conventional methods cannot support (Tene et al., 2024).

Challenges and considerations remain, particularly in terms of instructional design and technology adoption. While the potential for improved outcomes is substantial, teachers must be adequately trained to integrate AR, VR, and Metaverse tools effectively (Thangavel, 2025). Without sufficient training and pedagogical support, there is a risk of superficial implementation or underutilization. Additionally, technical limitations, costs, and infrastructure requirements may pose barriers to widespread adoption, particularly in schools with limited resources (Mondal & Mondal, 2025). Ensuring equitable access and addressing data privacy, cybersecurity, and digital well-being are critical considerations that educators and policymakers must address (Onu et al., 2023).

Finally, immersive technologies provide opportunities for future research. Studies should investigate long-term learning outcomes, the effectiveness of AI-driven personalized instruction, and the development of inclusive policies for equitable access (Tene et al., 2024). Research is also needed to examine how adaptive learning models within AR and Metaverse environments can cater to individual student needs across diverse educational contexts and disciplines (Zhang et al., 2022). Longitudinal studies assessing cognitive and non-cognitive outcomes, as well as the efficacy of immersive technologies in promoting collaboration, critical thinking, and problem-solving, will provide robust evidence for informed integration into STEM education (Onu et al., 2023).

In conclusion, incorporating AR, VR, and Metaverse technologies into STEM education offers significant pedagogical advantages, such as increased engagement, active learning, collaboration, skill enhancement, and evaluation opportunities. When used carefully and with the help of professional development, these immersive platforms could change the way we teach, make learning better, and get students ready for the complicated scientific and technological problems they will face in the future (Tene et al., 2024). Addressing challenges such as technical barriers, instructional design, and ethical considerations will be crucial to maximize the effectiveness and sustainability of these innovations in diverse educational contexts.

The Role of Educators and Digital Competencies

The successful integration of Metaverse and Augmented Reality into STEM education depends largely on the digital competencies and pedagogical readiness of educators. Teachers are not only facilitators of knowledge but also designers of learning experiences who must adapt instructional strategies to effectively leverage immersive technologies (Chiu & Li, 2023). This requires educators to go beyond technical proficiency and develop a pedagogical vision for how technologies can enhance inquiry, collaboration, and creativity. This encompasses developing skills in creating and editing digital content, understanding the educational advantages and challenges of AR integration, and employing effective pedagogical strategies to foster digital competencies (Baltynova et al., 2023) This requires a thorough comprehension of the integration of AR and VR into pedagogical approaches, the advancement of digital literacy among students, and the cultivation of critical thinking through technological interaction (Taggart et al., 2023). Nonetheless, obstacles such infrastructural deficiencies, fiscal limitations, and the necessity for extensive teacher training must be confronted to promote the extensive integration of these technologies in educational environments (Tene et al., 2024). To address these challenges, specialized professional development programs are crucial, providing educators with the requisite technological expertise and pedagogical strategies to effectively engage with immersive environments (Chiu & Li, 2023). Even though more and more people are interested in using immersive technologies in education, there isn't yet a comprehensive technique for teaching future STEM teachers how to use augmented reality in educational resources (Kiv et al., 2023). While significant research explores the impact of AR on student learning, studies focusing on teacher training and perceptions regarding AR implementation are notably scarce (Marín et al., 2023). This gap underscores the imperative for additional research into methodologies for teacher professional development and the augmentation of digital literacy, especially concerning the advent of emerging immersive technologies. Many teachers do not feel ready or do not have the skills they need to use technology effectively in the classroom. This shows a big gap between the need for technology and the readiness of teachers (Silva-Díaz et al., 2023). Therefore, addressing the need for teachers to integrate AR, VR, and mixed reality for real-life learning experiences is crucial for initial teacher education. Teacher education programs and policymakers should thus contemplate the integration of immersive experiences utilizing VR and AR to enhance pre-service teachers' understanding and assessment of their capacity to facilitate learning. This proactive strategy can cultivate heightened curiosity and a readiness to investigate innovative ICT practices among educators, as well as an acknowledgment of the importance of enhancing their digital competencies (Taggart et al., 2023).

The incorporation of immersive technologies, including Augmented Reality and the Metaverse, into STEM education represents a significant evolution in educational methodologies, requiring a robust framework for its execution (Tene et al., 2024). This integration demands not only an understanding of the technological tools themselves but also a nuanced appreciation for how they can fundamentally reshape content delivery and pedagogical strategies within STEM disciplines. The TPACK framework offers a robust conceptual model for understanding and guiding this integration, particularly by emphasizing the intricate interplay among technology, pedagogy, and content knowledge (Rahmawati et al., 2021). This framework provides a critical lens for educators to move beyond superficial technological adoption towards a deeper, more intentional integration that enhances student learning outcomes (Tene et al., 2024). The TPACK framework asserts that successful technology integration in education results from the dynamic interplay of these three fundamental knowledge domains, rather than their discrete application. This holistic approach is crucial for leveraging the full potential of AR and Metaverse tools, ensuring they are employed in ways that are both technologically sound and pedagogically effective (Bwalya et al., 2023). The framework underscores that teachers must possess a sophisticated blend of these knowledge domains to effectively design and implement learning experiences that transcend traditional boundaries, particularly when incorporating novel immersive technologies (Hsu et al., 2023). This involves developing specialized teacher competencies for utilizing AR in subjects like physics and creating VR-based educational tools for complex concepts such as projectile motion, as noted by recent research (Tene et al., 2024). As a result, it is very important to help teachers develop their design thinking abilities so that they can use AR in a meaningful way. This will allow them to creatively get around obstacles by changing or creating lesson plans and activities that are appropriate for different learning situations (Hsu et al., 2023). This thorough understanding guarantees that technology acts as a facilitator for profound learning, rather than simply as a pedagogical tool (Jimoyiannis, 2010). The TPACK framework, by delineating the complex relationships between these knowledge domains, offers a structured approach to address the challenges of integrating advanced digital technologies in education. This perspective highlights that merely understanding how a technology operates is insufficient; educators must also grasp its affordances for enriching instruction and promoting deeper learning (Michałko et al., 2022).

The swift advancement of immersive technologies, such as virtual reality, augmented reality, and mixed reality, offers unparalleled opportunities and considerable obstacles for contemporary education. These technologies present novel instructional methodologies that can augment student involvement, promote experiential learning, and grant access to hitherto unattainable situations (Taggart et al., 2023). However, to fully leverage their potential, educators require comprehensive professional development that extends beyond technical proficiency to encompass pedagogical integration and critical ethical considerations (Schwaiger et al., 2024). This involves providing teachers with both the technical abilities and the pedagogical content understanding essential for the efficient integration of these tools into their courses (Taggart et al., 2023). In addition, good professional development programs should not only teach teachers about the technical and pedagogical elements of new technologies, but also on the moral issues that come with them. This will help teachers teach pupils how to use them responsibly (Brandão et al., 2024). Moreover, professional development can empower educators to adapt to dynamic educational landscapes and address the evolving needs of their students, particularly concerning technological advancements (Mouta et al., 2024). Furthermore, professional development is crucial for enhancing educators' confidence and proficiency in utilizing these tools. Studies indicate that educators trained in immersive technology are more inclined to adopt new methodologies and promote favorable educational outcomes (Boel et al., 2023). Additionally, teachers must be aware of ethical and socio-cultural considerations, such as ensuring equitable access, safeguarding student data, and addressing potential issues of digital addiction or distraction (Schwaiger et al., 2024). Such comprehensive professional learning opportunities should be evidence-informed, long-lasting, contextualized, and team-oriented to maximize their effectiveness in promoting implementation and sustained use (Love et al., 2020). A crucial aspect of this preparation involves addressing the inherent technical demands of virtual learning environments and ensuring educators possess the specialized skills and resources for their effective design and implementation (Karcher et al., 2023).

This evolution requires a thorough comprehension of the strategic implementation of immersive technologies to enhance engagement, critical thinking, and collaborative problem-solving in scientific and technical fields. The successful integration of AR and Metaverse in STEM education hinges on educators' capacity to move beyond traditional teaching paradigms, embracing innovative pedagogical approaches that leverage the unique affordances of these technologies (Tene et al., 2024). This requires not only technical proficiency but also a refined pedagogical understanding to effectively bridge the gap between virtual enhancements and tangible learning outcomes (Velarde-Camaqui et al., 2024). The educational prospects within the Metaverse are extensive, offering virtual environments that can significantly enrich learning experiences through interactive modeling and experiential learning (Chen et al., 2024). These immersive technologies, such as augmented reality and virtual reality, make it possible to create realistic situations for complicated lab experiments or virtual field trips that would be too dangerous or hard to get to in real life (Tene et al., 2024). The metaverse, envisioned as an expansive digital ecosystem, enables individuals to transition from physical to virtual environments, demonstrating significant utility in educational contexts where practical experiments are difficult or perilous, such as space exploration, chemical experimentation, and flight simulation training (Almeman et al., 2025). This integration makes it possible to make complex, interactive learning spaces that give students hands-on experiences, which makes them more interested in and understand the material (Schwaiger et al., 2024). Moreover, the immersive features of AR and the Metaverse present unparalleled prospects for customized learning pathways, according to specific student requirements and learning preferences through individualized challenges and immediate feedback (Tene et al., 2024). These virtual platforms facilitate experiential learning, permitting students to investigate and engage in intricate, genuine tasks that are frequently inaccessible in the physical realm (Almeman et al., 2025).

Challenges, Limitations, and Ethical Considerations

Even though Augmented Reality (AR) and the Metaverse are known to have the potential to change STEM education by providing immersive and interactive learning experiences, there are still big problems that make it hard for them to be used widely and for a long time (Tene et al., 2024). These impediments encompass high implementation costs, inherent technical limitations, and notable resistance among educators to adopt these novel technologies (Thangavel, 2025). This resistance often stems from concerns regarding instructional design, increased workload, and a perceived lack of institutional support (Hsu et al., 2023). Moreover, the absence of standardized platforms and the considerable effort required for customizing virtual environments further complicate the adoption of AR/VR tools within educational frameworks (Terkaj et al., 2024).

A primary challenge involves the infrastructure and accessibility required for AR and Metaverse applications. High-performance hardware, reliable high-bandwidth networks, cloud storage solutions, and skilled personnel are essential for effective deployment, yet they impose significant financial and operational burdens on institutions, particularly in underserved regions (Huang & Tseng, 2025). Additionally, developing high-quality, curriculum-aligned AR/VR content requires expertise in 3D modeling, instructional design, and pedagogy, a process often constrained by time and resource limitations (Cabrera-Duffaut et al., 2024). This scarcity of tailored educational content frequently forces educators to adapt generic software or create bespoke solutions, both of which present substantial challenges.

Privacy, security, and digital ethics constitute another critical dimension of concern. AR and Metaverse applications collect large volumes of personal and behavioral data, necessitating robust safeguards to ensure compliance with data protection regulations such as GDPR or FERPA (Raman et al., 2025). The immersive and social nature of these environments introduces risks including identity misuse, exposure to harassment, and potential addiction, especially among younger learners (Zhang et al., 2022; Ramolia et al., 2024). Addressing these concerns requires comprehensive ethical frameworks, clear regulatory guidelines, and technological solutions such as blockchain for data traceability (Onu et al., 2023).

From a pedagogical standpoint, educators frequently encounter reluctance stemming from insufficient training and a lack of experience with AR/VR integration (Tene et al., 2024). To help teachers create and carry out immersive learning experiences, they need to have the right technical skills, pedagogical content understanding, and digital literacy. This is why effective professional development programs are so important (Schwaiger et al., 2024). These programs should also address ethical considerations, including equitable access, responsible use, and fostering safe collaborative environments (Brandão et al., 2024).

Furthermore, the digital divide remains a persistent limitation. Variations in institutional funding, access to reliable infrastructure, and availability of immersive content exacerbate inequities in STEM education, limiting opportunities for students in resource-constrained contexts (Silva-Díaz et al., 2023). Research indicates that despite the demonstrated benefits of AR and Metaverse platforms—including enhanced engagement, collaboration, and knowledge retention—these advantages may be unevenly realized without targeted interventions and institutional support (AlGerafi et al., 2023).

In sum, while AR and Metaverse technologies offer transformative opportunities for STEM education, their effective and equitable integration depends on addressing infrastructural, pedagogical, and ethical challenges. Future efforts should prioritize professional development, accessible content creation tools, standardized platforms, and rigorous data protection measures to ensure that these immersive environments can sustainably enhance learning outcomes (Qiu et al., 2023).

Conclusion and Future Research Directions

This chapter delves into the multifaceted benefits and challenges associated with integrating immersive technologies, specifically the Metaverse and Augmented Reality, into STEM education. This integration holds substantial promise for revolutionizing traditional pedagogical approaches by fostering dynamic and interactive learning environments (Tene et al., 2024). Augmented reality has become a popular technology, and researchers often look into how it might help students stay interested and do better in school. Studies show that immersive technologies like AR and VR make it much easier to understand difficult ideas, boost student engagement, and make group learning more interesting (Tene et al., 2024). Moreover, integrating social and ethical values into education has been highlighted as essential for fostering students' holistic development (Ergün Kaplan & Sulak, 2017). These technologies facilitate active learning through simulations and interactive experiences, promoting critical thinking and knowledge retention across diverse educational domains (AlGerafi et al., 2023). Furthermore, AR's capability to overlay digital information onto the real world allows for powerful visualization of abstract scientific and mathematical concepts, particularly in engineering education, where deep knowledge and problem-solving skills are paramount (Suhail et al., 2024). This immersive approach has been shown to enhance academic performance and increase proficiency in STEM capabilities by providing hands-on learning experiences. Specifically, AR reduces cognitive load and enhances imaginative capabilities, making complex scientific fundamentals more accessible and engaging for learners. The utility of AR extends beyond visualization, enabling gamified and collaborative learning experiences, particularly within primary school curricula (Tene et al., 2024). The broader application of both Augmented Reality and Virtual Reality across educational levels underscores their capacity to foster better knowledge retention and skill development in fields ranging from medicine to language learning, despite existing limitations such as high costs and technical constraints (Thangavel, 2025).

Even if these technologies have a lot of potential, there are still problems with interoperability, standardization, and the need for more solid proof of their effectiveness. This means that further research and development are needed to make sure that these technologies have a place in education (Onu et al., 2023). Moreover, significant barriers impede widespread adoption, including high implementation costs, inherent technical limitations, and resistance among educators due to concerns about instructional design, increased workload, and perceived lack of institutional support (Thangavel, 2025). The absence of standardized platforms and the substantial effort required to customize virtual environments further complicate the integration of AR/VR tools within educational frameworks (Terkaj et al., 2024).

The swift advancement of immersive technologies demands a comprehensive examination of their enduring impacts on student learning and development, including cognitive aspects such as knowledge acquisition and retention, as well as non-cognitive elements like motivation and engagement (Raman et al., 2025). Previous meta-analyses indicate that AR positively influences learning outcomes, particularly when considering spatial abilities (Cao & Yu, 2023). Beyond initial engagement, immersive platforms foster improved knowledge retention and practical skill development by transporting students to virtual environments that facilitate experiential learning (Shankar, 2023). Initial research on the Metaverse underscores the necessity of investigating students' sense of presence and the emotional dimensions linked to immersive experiences, transcending mere cognitive outcomes (Çelik & Baturay, 2023; Jung et al., 2023). Subsequent study ought to investigate the relationship between cognitive load reduction and tangible learning outcomes, individual variances including prior knowledge and learning preferences, as well as the versatility of immersive technology across many academic disciplines (Poupard et al., 2025).

Future study should investigate the long-term educational outcomes of integrating AR and the Metaverse, the impact of AI-driven personalization, and the formulation of inclusive policies to guarantee fair access. When designing a curriculum, it's important to think about ways to make it last that are in line with national education goals. Subsequent inquiries ought to examine adaptive educational frameworks that utilize immersive technologies beyond simple interactive instruments, emphasizing tailored learning experiences that address the unique demands and preferences of each student (Tene et al., 2024). Additionally, the efficacy of Metaverse applications in educational settings, particularly regarding interoperability and standardized content development, requires further empirical validation (Onu et al., 2023). Longitudinal research are crucial for evaluating the enduring effects of AR and the Metaverse on cognitive and non-cognitive characteristics across various age groups and educational levels (Zhang et al., 2022).

In sum, the integration of AR and the Metaverse into STEM education presents transformative opportunities to foster immersive, interactive, and engaging learning experiences, while simultaneously posing infrastructural, pedagogical, and ethical challenges. It is important for educators, policymakers, and industry leaders to work together to create strong teaching frameworks and thorough teacher training programs. This will make sure that these immersive technologies live up to their potential to improve student learning outcomes in a variety of educational settings (Thangavel, 2025).

References

Abdelmoneim, R., Hassounah, E., & Radwan, E. (2022). Effectiveness of virtual laboratories on developing expert thinking and decision-making skills among female school students in Palestine. *Eurasia Journal of Mathematics Science and Technology Education*, *18*(12). https://doi.org/10.29333/ejmste/12708

Aguilera, D., Lupiáñez, J. L., González, J. M. V., & Palacios, F. J. P. (2021). In search of a long-awaited consensus on disciplinary integration in STEM education. *Mathematics*, *9*(6), 597. https://doi.org/10.3390/math9060597

Akçayır, M., & Akçayır, G. (2017). Advantages and challenges associated with augmented reality for education: A systematic review of the literature. *Educational Research Review*, *20*, 1-11. https://doi.org/10.1016/j.edurev.2016.11.002

AlGerafi, M. A. M., Zhou, Y., Oubibi, M., & Wijaya, T. T. (2023). Unlocking the potential: A comprehensive evaluation of augmented reality and virtual reality in education. *Electronics*, *12*(18), 3953. https://doi.org/10.3390/electronics12183953

Almeman, K., Ayeb, F. E., Berrima, M., Issaoui, B., & Morsy, H. (2025). The integration of AI and metaverse in education: A Systematic Literature Review. *Applied Sciences*, *15*(2), 863. https://doi.org/10.3390/app15020863

Ananikov, V. P. (2024). Top 20 influential AI-based technologies in chemistry. *Artificial Intelligence Chemistry*, *2*(2), 100075. https://doi.org/10.1016/j.aichem.2024.100075

Baltynova, A., Kamariyash, K., Muzdbaeva, T., Bolat, Y., Beleukhanova, K., Zharikova, D., & Mollakuqe, E. (2023). Pedagogical conditions for the training of future teachers based on digital educational technologies. *International Journal of Emerging Technologies in Learning (iJET)*, *18*(18), 121. https://doi.org/10.3991/ijet.v18i18.43209

Bermejo, B. G., Juiz, C., Cortes, D., Oskam, J., Moilanen, T., Loijas, J., Govender, P., Hussey, J., Schmidt, A. L., Burbach, R., King, D. B., O'Connor, C., & Dunlea, D. (2023). AR/VR teaching-learning experiences in higher education institutions (HEI): A systematic literature review. *Informatics*, *10*(2), 45. https://doi.org/10.3390/informatics10020045

Boel, C., Dekeyser, K., Lemal, M., Rotsaert, T., Valcke, M., Schellens, T., & Struyf, D. (2023). Towards a framework for a nation-wide implementation of augmented, virtual and mixed reality in K-12 technical and vocational education. *TechTrends*, *68*(2), 295. https://doi.org/10.1007/s11528-023-00925-y

Brandão, A., Pedro, L., & Zagalo, N. (2024). Teacher professional development for a future with generative artificial intelligence – an integrative literature review. *Digital Education Review*, *45*, 151. https://doi.org/10.1344/der.2024.45.151-157

Bwalya, A., Rutegwa, M., Tukahabwa, D., & Mapulanga, T. (2023). Enhancing pre-service biology teachers' technological pedagogical content knowledge through a tpack-based technology integration course. *Journal of Baltic Science Education*, *22*(6), 956. https://doi.org/10.33225/jbse/23.22.956

Cabrera-Duffaut, A., Llorente, A. M. P., & Rodríguez, A. I. (2024). Immersive learning platforms: analyzing virtual reality contribution to competence development in higher education—a systematic literature review. *Frontiers in Education*, *9*. https://doi.org/10.3389/feduc.2024.1391560

Cañavate, J., Martinez-Marroquin, E., & Colom, X. (2025). Engineering a sustainable future through the integration of generative ai in engineering education. *Sustainability*, *17*(7), 3201. https://doi.org/10.3390/su17073201

Cao, W., & Yu, Z. (2023). The impact of augmented reality on student attitudes, motivation, and learning achievements—a meta-analysis (2016–2023). *Humanities and Social Sciences Communications*, *10*(1). https://doi.org/10.1057/s41599-023-01852-2

Çelik, F., & Baturay, M. H. (2024). The effect of metaverse on L2 vocabulary learning, retention, student engagement, presence, and community feeling. *BMC Psychology*, *12*(1), 58. https://doi.org/10.21203/rs.3.rs-3763892/v1

Chen, G., Jin, Y., & Chen, P. (2024). Development of a platform for state online education services: Design concept based on meta-universe. *Education and Information Technologies*, *29*(17), 23605. https://doi.org/10.1007/s10639-024-12792-y

Chin, K.-Y., Kao, Y.-C., & Wang, C.-S. (2020). Effects of augmented reality technology in a mobile touring system on university students' learning performance and interest. *Australasian Journal of Educational Technology*, 27. https://doi.org/10.14742/ajet.5841

Chiu, T. K. F., & Li, Y. (2023). How can emerging technologies impact STEM education? *Journal for STEM Education Research*, *6*(3), 375. https://doi.org/10.1007/s41979-023-00113-w

Dahan, N. A., Al-Razgan, M., Al-Laith, A., Alsoufi, M. A., Al-Asaly, M. S., & Alfakih, T. (2022). Metaverse framework: A case study on e-learning environment (ELEM). *Electronics*, *11*(10), 1616. https://doi.org/10.3390/electronics11101616

Dwivedi, Y. K., Hughes, L., Baabdullah, A. M., Ribeiro-Navarrete, S., Giannakis, M., Al-Debei, M. M., Dennehy, D., Metri, B., Buhalis, D., Cheung, C. M. K., Conboy, K., Doyle, R., Dubey, R., Dutot, V., Felix, R., Goyal, D. P., Gustafsson, A., Hinsch, C., Jebabli, I., … Wamba, S. F. (2022). Metaverse beyond the hype: Multidisciplinary perspectives on emerging challenges, opportunities, and agenda for research, practice and policy. *International Journal of Information Management*, *66*, 102542. https://doi.org/10.1016/j.ijinfomgt.2022.102542

Ergün Kaplan, S. &. Sulak, S. A., (2017). The examination of perception of social values of elementary school students according to different variables. *Bartın University Journal of Faculty of Education, 6(3), 840-858*. https://doi.org/10.14686/buefad.292038

Hsu, H.-P., Cheah, Y. H., & Hughes, J. E. (2023). A case study of a secondary biology teacher's pedagogical reasoning and action with augmented reality technology. *Education Sciences*, *13*(11), 1080. https://doi.org/10.3390/educsci13111080

Huang, T., & Tseng, H. (2025). Extended reality in applied sciences education: A systematic review. *Applied Sciences*, *15*(7), 4038. https://doi.org/10.3390/app15074038

Huynh-The, T., Gadekallu, T. R., Wang, W., Yenduri, G., Ranaweera, P., Pham, Q., Costa, D. B. da, & Liyanage, M. (2023). Blockchain for the metaverse: A Review. *Future Generation Computer Systems*, *143*, 401. Elsevier BV. https://doi.org/10.1016/j.future.2023.02.008

Ibáñez, M. B., & Kloos, C. D. (2018). Augmented reality for STEM learning: A systematic review. *Computers & Education*, *123*, 109. https://doi.org/10.1016/j.compedu.2018.05.002

Iqbal, M. Z., & Campbell, A. G. (2022). AGILEST approach: Using machine learning agents to facilitate kinesthetic learning in STEM education through real-time touchless hand interaction. *Telematics and Informatics Reports*, *9*, 100034. https://doi.org/10.1016/j.teler.2022.100034

Irwanto, I. (2021). Research trends in technological pedagogical content knowledge (TPACK): A systematic literature review from 2010 to 2021. *European Journal of Educational Research*, 2045. https://doi.org/10.12973/eu-jer.10.4.2045

Jimoyiannis, A. (2010). Designing and implementing an integrated technological pedagogical science knowledge framework for science teachers professional development. *Computers & Education*, *55*(3), 1259. https://doi.org/10.1016/j.compedu.2010.05.022

Jung, T., Cho, J., Han, D. D., Ahn, S. J., Gupta, M., Das, G., Heo, C. Y., Loureiro, S. M. C., Σιγάλα, M., Trunfio, M., Taylor, A., & Dieck, M. C. tom. (2023). Metaverse for service industries: Future applications, opportunities, challenges and research directions. *Computers in Human Behavior*, *151*, 108039. https://doi.org/10.1016/j.chb.2023.108039

Kalemkuş, J., & Kalemkuş, F. (2024). The effects of designing scientific experiments with visual programming language on learning outcomes. *Science & Education*. https://doi.org/10.1007/s11191-024-00546-8

Karcher, A., Arnold, D., & Kuhlenkötter, B. (2023). Development of a guideline under didactical aspects for the use of immersive virtual learning environments. *Journal of Formative Design in Learning*, *7*(2), 98. https://doi.org/10.1007/s41686-023-00085-5

Kelley, T. R., & Knowles, J. G. (2016). A conceptual framework for integrated STEM education. *International Journal of STEM Education*, *3*(1). https://doi.org/10.1186/s40594-016-0046-z

Kim, J.-Y., & Choi, J. K. (2025). Effects of AR on cognitive processes: An experimental study on object manipulation, eye-tracking, and behavior observation in design education. *Sensors*, *25*(6), 1882. https://doi.org/10.3390/s25061882

Koklu, N., & Sulak, S. A. (2021). World geography with augmented reality. *International Journal of Progressive Sciences and Technologies*, *29*(1), 94-108.

Lampropoulos, G., Keramopoulos, E., Diamantaras, K., & Evangelidis, G. (2022). Augmented reality and gamification in education: A systematic literature review of research, applications, and empirical studies. *Applied Sciences*, *12*(13), 6809. https://doi.org/10.3390/app12136809

Lastrucci, A., Wandael, Y., Barra, A., Ricci, R., Maccioni, G., Pirrera, A., & Giansanti, D. (2024). Exploring augmented reality integration in diagnostic imaging: Myth or reality? *Diagnostics*, *14*(13), 1333. https://doi.org/10.3390/diagnostics14131333

Li, M., & Li, B. (2024). Unravelling the dynamics of technology integration in mathematics education: A structural equation modelling analysis of TPACK components. *Education and Information Technologies*, *29*(17), 23687. https://doi.org/10.1007/s10639-024-12805-w

Lin, H., Wan, S., Gan, W., Chen, J., & Chao, H. (2022). Metaverse in education: Vision, opportunities, and challenges. *2021 IEEE International Conference on Big Data (Big Data)*, 2857. https://doi.org/10.1109/bigdata55660.2022.10021004

Love, M., Simpson, L. A., Golloher, A., Gadus, B., & Dorwin, J. (2020). Professional development to increase teacher capacity for the use of new technologies. *Intervention in School and Clinic*, *56*(2), 115. https://doi.org/10.1177/1053451220914886

Lunding, M. S., Grønbæk, J. E. S., Grymer, N., Wells, T., Houben, S., & Petersen, M. G. (2023). Reality and beyond: proxemics as a lens for designing handheld collaborative augmented reality. *Proceedings of the ACM on Human-Computer Interaction*, *7*, 21. https://doi.org/10.1145/3626463

Lyngdorf, N. E. R., Jiang, D., & Du, X. (2024). Frameworks and models for digital transformation in engineering education: a literature review using a systematic approach. *Education Sciences*, *14*(5), 519. https://doi.org/10.3390/educsci14050519

Mansour, N., Aras, C. Y., Staarman, J. K., & Alotaibi, S. B. (2024). Embodied learning of science concepts through augmented reality technology. *Education and Information Technologies*. https://doi.org/10.1007/s10639-024-13120-0

Marín, J. A. M., López-Belmonte, J., Sánchez, S. P., & Moreno-Guerrero, A.-J. (2023). Attitudes towards the development of good practices with augmented reality in secondary education teachers in Spain. *Technology Knowledge and Learning*, *28*(4), 1443. https://doi.org/10.1007/s10758-023-09671-9

Marzuki, O. F., Lih, E. T. Y., Abdullah, W. N. Z. Z., Khairuddin, N., Inai, N. H., Saad, J. B. M., & Aziz, M. H. A. (2024). Innovating education: A comprehensive review of STEM education approaches. *International Journal of Academic Research in Progressive Education and Development*, *13*(1). https://doi.org/10.6007/ijarped/v13-i1/20490

Michałko, A., Campo, A., Nijs, L., Leman, M., & Dyck, E. V. (2022). Toward a meaningful technology for instrumental music education: Teachers' voice. *Frontiers in Education*, *7*. https://doi.org/10.3389/feduc.2022.1027042

Mondal, H., & Mondal, S. (2025). Adopting augmented reality and virtual reality in medical education in resource-limited settings: constraints and the way forward. *AJP Advances in Physiology Education*. https://doi.org/10.1152/advan.00027.2025

Mouta, A., Sánchez, E. M. T., & Llorente, A. M. P. (2024). Comprehensive professional learning for teacher agency in addressing ethical challenges of AIED: Insights from educational design research. *Education and Information Technologies*. https://doi.org/10.1007/s10639-024-12946-y

Mystakidis, S., Christopoulos, A., & Pellas, N. (2021). A systematic mapping review of augmented reality applications to support STEM learning in higher education. *Education and Information Technologies*, *27*(2), 1883. https://doi.org/10.1007/s10639-021-10682-1

Onu, P., Pradhan, A., & Mbohwa, C. (2023). Potential to use metaverse for future teaching and learning. *Education and Information Technologies*, *29*(7), 8893. https://doi.org/10.1007/s10639-023-12167-9

Özçakır, B., & Çakıroğlu, E. (2021). An augmented reality learning toolkit for fostering spatial ability in mathematics lesson: design and development. *European Journal of Science and Mathematics Education*, *9*(4), 145. https://doi.org/10.30935/scimath/11204

Palada, B., Chandan, V. S., Gowda, C. P., & Nikitha, Prof. (2024). The role of augmented reality (AR) in education. *International Journal for Research in Applied Science and Engineering Technology*, *12*(3), 1400. https://doi.org/10.22214/ijraset.2024.59079

Petrov, P. D., & Atanasova, T. (2020). The effect of augmented reality on students' learning performance in stem education. *Information*, *11*(4), 209. https://doi.org/10.3390/info11040209

Poupard, M., Larrue, F., Sauzéon, H., & Tricot, A. (2025). A systematic review of immersive technologies for education: effects of cognitive load and curiosity state on learning performance. *HAL (Le Centre Pour La Communication Scientifique Directe)*. https://hal.archives-ouvertes.fr/hal-03906797

Qiu, Y., Isusi-Fagoaga, R., & García-Aracil, A. (2023). Perceptions and use of metaverse in higher education: A descriptive study in China and Spain. *Computers and Education Artificial Intelligence*, *5*, 100185. https://doi.org/10.1016/j.caeai.2023.100185

Rahmawati, A., Suryani, N., Akhyar, M., & Sukarmin, S. (2021). Vocational teachers' perspective toward Technological Pedagogical Vocational Knowledge. *Open Engineering*, *11*(1), 390. https://doi.org/10.1515/eng-2021-0040

Raman, R., Kowalski, R. M., & Achuthan, K. (2025). Metaverse technologies and human behavior: insights into engagement, adoption, and ethical challenges. *Computers in Human Behavior Reports*, 100712. https://doi.org/10.1016/j.chbr.2025.100712

Rusmin, L., Misrahayu, Y., Pongpalilu, F., Radiansyah, R., & Dwiyanto, D. (2024). Critical thinking and problem-solving skills in the 21st century. *Deleted Journal*, *1*(5), 144. https://doi.org/10.59613/svhy3576

Schwaiger, M., Krajnčan, M., Vukovič, M., Jenko, M., & Doz, D. (2024). Educators' opinions about VR/AR/XR: An exploratory study. *Education and Information Technologies*. https://doi.org/10.1007/s10639-024-12808-7

Shankar, V. T. A. U. (2023). Impact of virtual reality (vr) and augmented reality (ar) in education. *Tuijin Jishu/Journal of Propulsion Technology*, *44*(4), 1310. https://doi.org/10.52783/tjjpt.v44.i4.1014

Shirazi, A., & Behzadan, A. H. (2015). Content delivery using augmented reality to enhance students' performance in a building design and assembly project. *Advances in Engineering Education*, *4*(3), n3.

Silva-Díaz, F., Carrillo-Rosúa, J., Ferrer, G. F., Carmona, R. M., & Narváez, R. (2023). Valoración de tecnologías inmersivas y enfoque STEM en la formación inicial del profesorado. *RIED Revista Iberoamericana de Educación a Distancia*, *27*(1), 139. https://doi.org/10.5944/ried.27.1.37688

Smith, K., Maynard, N., Berry, A., Stephenson, T., Spiteri, T., Corrigan, D., Mansfield, J., Ellerton, P., & Smith, T. C. (2022). Principles of problem-based learning (pbl) in stem education: using expert wisdom and research to frame educational practice. *Education Sciences*, *12*(10), 728. https://doi.org/10.3390/educsci12100728

Sommerauer, P., & Müller, O. (2014). Augmented reality in informal learning environments: A field experiment in a mathematics exhibition. *Computers & Education*, *79*, 59. https://doi.org/10.1016/j.compedu.2014.07.013

Suhail, N., Bahroun, Z., & Ahmed, V. (2024). Augmented reality in engineering education: enhancing learning and application. *Frontiers in Virtual Reality*, *5*. https://doi.org/10.3389/frvir.2024.1461145

Sulak, S. A., & Koklu, N. (2024). Bibliometric Analysis of Publications Related to Augmented Reality in Education in The Last 20 Years. Advances In Education Sciences. *Advances in Education Sciences, M. Dalkılıç and O. Soslu, Eds. Platanus Publishing, 31-58*. https://doi.org/10.5281/zenodo.14582661

Sviridova, E., Yastrebova, E., Bakirova, G., & Rebrina, F. (2023, October). Immersive technologies as an innovative tool to increase academic success and motivation in higher education. *In Frontiers in Education* (Vol. 8). https://doi.org/10.3389/feduc.2023.1192760

Taggart, S., Roulston, S., Brown, M., Donlon, E., Cowan, P., Farrell, R., & Campbell, A. A. (2023). Virtual and augmented reality and pre-service teachers: Makers from muggles? *Australasian Journal of Educational Technology*, 1. https://doi.org/10.14742/ajet.8610

Tene, T., Tixi, J. A. M., Robalino, M. de L. P., Salazar, M. J. M., Gómez, C.

V., & Bellucci, S. (2024). Integrating immersive technologies with STEM education: a systematic review. *Frontiers in Education*, *9*. Frontiers Media. https://doi.org/10.3389/feduc.2024.1410163

Terkaj, W., Urgo, M., Kovács, P., Tóth, E., & Mondellini, M. (2024). A framework for virtual learning in industrial engineering education: development of a reconfigurable virtual learning factory application. *Virtual Reality*, *28*(3). https://doi.org/10.1007/s10055-024-01042-8

Thangavel, S. (2025). Revolutionizing education through augmented reality (ar) and virtual reality (vr): innovations, challenges and future prospects. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.5195697

Thibaut, L., Ceuppens, S., Loof, H. D., Meester, J. D., Goovaerts, L., Struyf, A., Pauw, J. B., Dehaene, W., Deprez, J., Cock, M. D., Hellinckx, L., Knipprath, H., Langie, G., Struyven, K., Velde, D. van de, Petegem, P. V., & Depaepe, F. (2018). Integrated STEM education: A systematic review of instructional practices in secondary education. *European Journal of STEM Education*, *3*(1). https://doi.org/10.20897/ejsteme/85525

Tu, X., & Silva, B. de C. e. (2025). Are we ready for the metaverse? Implications, legal landscape, and recommendations for responsible development. *Deleted Journal*, *4*(1). https://doi.org/10.1007/s44206-025-00163-0

Velarde-Camaqui, D., Celaya-Ramírez, R., Contreras-Fuentes, Y., & Sanabria-Z, J. (2024). Enhancing STEAM education through augmented reality: the EduAR open platform experience. *Frontiers in Education*, *9*. https://doi.org/10.3389/feduc.2024.1391803

Zhang, X., Chen, Y., Hu, L., & Wang, Y. (2022). The metaverse in education: Definition, framework, features, potential applications, challenges, and future research topics. *Frontiers in psychology*, *13*, 1016300. https://doi.org/10.3389/fpsyg.2022.1016300

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