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Review Article

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Engineering Education Meets the Metaverse

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Abstract The metaverse, a collective virtual shared space created by the convergence of virtually enhanced physical reality and persistent virtual space, encompassing all virtual worlds, augmented realities, and the Internet, offers a unique platform for experiential learning and collaborative education. This study used the Web of Science, Google Scholar, and Scopus via Publish or Perish for source searching, with VOSviewer employed for bibliometric visualization. Following the PRISMA protocol, the study systematically reviewed relevant literature to address the following research questions: (1) What specific fields within engineering education incorporate Metaverse-based learning? (2) Which tools, technologies, or software platforms are employed in these practices? (3) What teaching strategies or educational frameworks are utilized in this context? (4) How do collaboration and interaction between humans and computers take place within the Metaverse? (5) What is the role of digital twins in Metaverse education? This review investigates the metaverse's role in engineering education, highlighting both its positive impacts and potential drawbacks.

Keywords Metaverse · Engineering Education · Virtual Reality · E-Learning

Author Note This paper is part of the research project *Metaverse Approach for a New Generation of Engineering Education and Collaborative Learning (MAGURA)*, conducted under Project No. BG-RRP-2.004-0006-C02, titled *Development of Research and Innovation at Trakia University in Service of Health and Sustainable Well-being.*

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Introduction

The concept of the Metaverse gained significant attention in 2021, with companies like Microsoft, Samsung, and ByteDance introducing Metaverse platforms. By bridging the gap between the physical and virtual worlds, the Metaverse overcomes the limitations of traditional 2D e-learning environments. It integrates technologies such as Virtual Reality (VR) and Augmented Reality (AR) to create immersive experiences (Wu & Gao, 2022; Zhonggen, 2023; Zonaphan et al., 2022). In particular, VR allows users to interact with digital environments and engage with others in real-time, fostering a connected social ecosystem across various platforms (Mystakidis, 2022). Education has emerged as a key area of innovation within the Metaverse, significantly enhancing students' cognitive engagement (Aşıksoy, 2023; Bradbury, 2022).

The Metaverse comprises a network of technology devices and platforms intertwined with IoT, Blockchain, Artificial Intelligence, Big Data Analytics, and other advanced industries, including education (Zhou, 2022). It offers numerous benefits, including improved user experiences, seamless collaboration and communication, virtual commerce opportunities, support for training and education, and avenues for entertainment, social interaction, and research innovation. However, the Metaverse remains a nascent concept (Deng, 2023).

In education, the Metaverse can serve as a platform for hosting virtual classrooms, delivering interactive learning experiences, and facilitating training simulations in fields such as healthcare, aviation, and engineering. These features make it particularly valuable for distance education and skills training. Despite this potential, questions about the Metaverse's adoption and impact on education remain underexplored (De Felice et al., 2023). For widespread adoption, technological advancements, legal frameworks, and regulatory oversight are necessary (Deng, 2023). Nevertheless, utilizing the Metaverse to train engineers capable of meeting international standards and embracing digital transformation represents a forward-looking strategy (Thongprasit & Piriyasurawong, 2022). Among the tools used to validate various Metaverse models, SmartPLS (PLS-SEM) is the most prominent (Flores-Castañeda et al., 2024).

The metaverse, a hypothetical virtual space where humans interact with digital environments, has gained attention as a transformative concept in industries as diverse as education, healthcare, and business. Therefore, it is worth exploring the evolution of the Metaverse in education, the way it has been designed and the trends in its research over the years, as well as its place in engineering education.

With the research and review, we answered the following research questions:

- RQ1. In what areas of engineering education is Metaverse learning practiced?
- RQ2. Which tools, technologies, or software platforms are employed in these practices?
- RQ3. What teaching strategies or educational frameworks are used in this context?
- RQ4. How do collaboration and interaction between humans and computers occur within the Metaverse?
- RQ5. What is the role of digital twins in Metaverse education?

Scientific research and analysis are essential for selecting appropriate software and designing teaching materials to experiment with engineering education in the Metaverse. This initiative is set to be implemented at the Faculty of Engineering and Technology - Yambol as part of the *Metaverse Approach for a New Generation of Engineering Education and Collaborative Learning (MAGURA)* project, under Project No. BG-RRP-2.004-0006-C02, titled Development of research and innovation at Trakia University in service of health and sustainable well-being.

The study aims to explore the Metaverse's potential as a tool in engineering education (EE), employing content and bibliometric analyses to identify research trends, focal points, and gaps within this domain. Notably, few studies have addressed mobile learning, hybrid learning, or microlearning scenarios, and no studies to date have specifically examined the application of the Metaverse in engineering education.

The findings offer a roadmap for future research to enhance Metaverse adoption in education globally and improve teaching and learning experiences within this virtual environment. By conducting a comprehensive bibliometric analysis of the field, this paper sheds light on research trends, academic contributions, and the conceptual themes of scholarly work related to the Metaverse in education. It represents a significant step toward understanding the evolving research landscape and advancing the integration of the metaverse into educational practices.

Research Methods

Sources of Data and Search Methods

This study employs a mixed-methods approach, combining both quantitative and qualitative synthesis, to review educational research related to the Metaverse. Traditional systematic reviews, while valuable, often risk introducing reporting biases and subjective interpretations of findings (He et al., 2017). To address this, the study adopts a systematic review framework incorporating bibliometric and content analysis, which allows for a scientific evaluation of the knowledge base and the evolution of the topic (Tlili et al., 2022). This review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines for structure and methodology (Moher et al., 2010).

This systematic review analyzes Metaverse-related educational research sourced from databases such as Web of Science, Google Scholar, and Scopus. Search queries utilized keywords including "(metaverse OR virtual reality OR VR OR extended reality OR XR) AND (engineering education AND immersive education OR immersive learning OR immersive teaching) NOT (artificial intelligence OR deep learning OR machine learning)." These keywords were chosen based on the authors' expertise and experience. The search produced a list of 4,386 publications from the Web of Science database.

To broaden the scope, Harzing's Publish or Perish tool was used with the same keywords to extract an additional 1,200 publications from Google Scholar (1,000 records) and Scopus (200 records), covering the period between 2013 and February 2024. Although data from 2024 is incomplete and limited to publications up to March, it is included to highlight a clear trend of increasing research activity in the field.

The analysis focuses on citation networks, authors' research areas, and the content of the selected papers. This bibliometric approach results in the development of a comprehensive model detailing key elements such as authors, article titles, keywords, and abstracts. By aligning these elements with studies on engineering education in the Metaverse, the study establishes stronger connections within the research taxonomy and provides valuable insights into this emerging field.

Data cleaning

Certain publications were excluded based on the following criteria: (1) failure to address the research questions related to the Metaverse in education, particularly in engineering education; (2) lack of relevance to the topics associated with the research questions; (3) absence from peer-reviewed conferences; and (4) unavailability online. After applying these criteria, 85 studies from the Web of Science, Scopus, and Google Scholar databases were included in the analysis.

The study employed both content analysis and bibliometric analysis to interpret the data, ensuring a comprehensive perspective and enhancing the validity of the findings through data triangulation. VOSviewer software was utilized to generate distance-based co-occurrence maps, where terms derived from keywords, titles, and abstracts were grouped and visualized based on their relatedness within a similarity matrix (Van Eck & Waltman, 2010).

Results

Features of the Selected Literature

Figure 1 illustrates the literature identification procedure. Initially, 4386 records were retrieved—1000 from Google Scholar and 200 from Scopus through the WoSCC database. After removing ineligible entries, the titles and abstracts of 2271 records were manually evaluated, and 653 additional records were excluded. Based on the predefined study questions, 150 records were extracted. The final review included 85 scientific publications after applying the exclusion criteria. To understand publication trends, important authors, organizations, and study fields, the data were thoroughly examined.

Filtering of the results

Only open-access articles were included in the further analysis because they are peer-reviewed and can be accessed in scientific databases. For this reason, only Article 2243 (Table 1) and Review Article 251 were included in the following analyses.

Web of Science articles were filtered according to the following criteria:

- by years for the period from 2013 to m.02.2024.
- by types of documents – Articles; Review Articles; and some Proceeding Paper articles that were reviewed; Early Access and Book chapters were scanned according to titles and abstracts to assess the inclusion of some of them.
- Research area: Computer Science, Education Educational Research, Engineering, Science Technology, and Automation Control Systems;
- Web of Science Categories.

Table 1

Type of Publications

Document Types	Record Count	% of 4386
Article	2243	51.140
Book Chapters	36	0.798
Early Access	221	5.039
Proceeding Paper	1920	43.776
Review Article	251	5.723

A search was also conducted through Google Scholar and Scopus and the results were combined. A total of 2271 articles were included in the final set. They were analyzed by VOSviewer. VOS creates a map based on text data to create a term co-occurrence map.

The search for "Engineering Education in Metaverse" across various academic databases yielded 4,386 results, with a total of 39,139 citations and an average of 8.92 citations per item. The h-index, which measures both the productivity and citation impact of the publications, is 76 (Table 2).

Table 2
Publication by Years

Publication Years	Web of Science		Google Scholar	
	Record Count	% of 4386	Record Count	% of 997
2024	307	7.000	52	5,22
2023	1324	30.187	158	15,85
2022	846	19.289	172	17,25
2021	524	11.947	160	16,05
2020	352	8.026	145	14,54
2019	327	7.456	119	11,94
2018	233	5.312	60	6,02
2017	180	4.104	37	3,71
2016	107	2.440	29	2,91
2015	91	2.075	31	3,11
2014	47	1.072	19	1,91
2013	48	1.094	15	1,5

There has been a noticeable trend of increasing publication volume recently in both Web of Science and Google Scholar, peaking in 2023 and 2022, respectively. The highest record count was observed in 2023 for Web of Science (1324 records, 30.187%) and in 2022 for Google Scholar (172 records, 17.25%). This indicates significant recent interest and activity in the field. Publications before 2016 are relatively sparse, indicating that the intersection of engineering education and the metaverse is a relatively new field of study.

Comparative Analysis of Data Sources-Web of Science vs. Google Scholar:

Coverage: The Web of Science consistently has higher record counts compared to Google Scholar for the same years. This might be due to the more stringent inclusion criteria and indexing practices of the Web of Science.

Percentages: The percentages of total records vary, with Google Scholar generally showing a higher percentage in recent years (e.g., 2022 and 2021), suggesting broader indexing or more diverse sources included in Google Scholar.

Implications for Engineering Education and the Metaverse:

Emerging Interest: The data indicates a growing interest in integrating metaverse concepts with engineering education, especially in the last five years.

Research Focus: The peak recently suggests active research and possibly significant advancements or findings being made in this intersection.

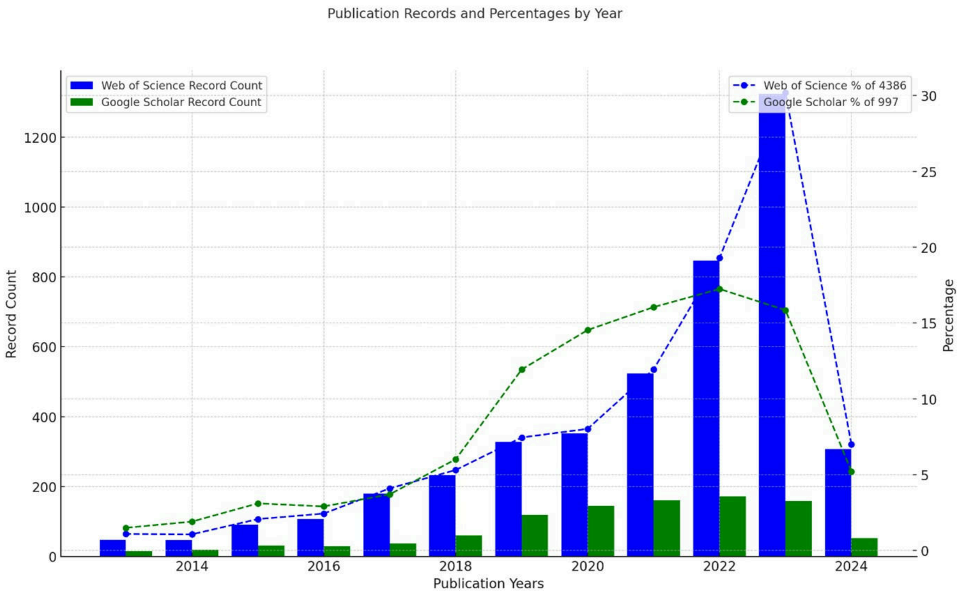
Future Trends: The slight dip in 2024 could suggest either a stabilization in the publication rate or a shift in research focus. Continuous monitoring of publication trends will be necessary to understand the evolving landscape.

Table 2 provides a clear picture of the growing academic interest in the intersection of engineering education and the metaverse, particularly in the last few years. The analysis indicates that the topic has gained significant traction, likely due to technological advancements and the increasing relevance of immersive and virtual learning environments. Researchers and educators should consider these trends when exploring new studies or educational initiatives in this dynamic field.

This chart (Figure 1) helps to visualize how the share of publications varies between the two databases over time, providing a clearer comparison based on relative proportions rather than absolute numbers.

Figure 1

Publication Records and Percentages by Year



PRISMA protocol results

The study is based on a systematic review approach performed by means of the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) protocol, to reveal the effect of the Metaverse in the field of engineering education (Page et al., 2021. n71; Page et al., 2021. n160). A PRISMA's rigorous protocol is used to systematically review academic articles indexed in different databases Web of Science, Scopus, and Google Scholar.

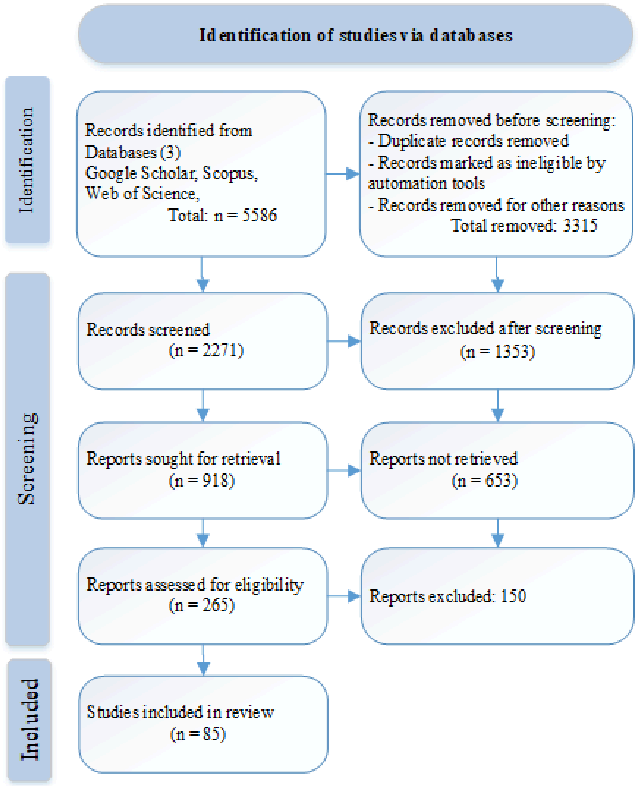
After conducting our initial searches for relevant studies, you can use the PRISMA protocol to organize and report your findings. Here is a step-by-step guide on how to use the PRISMA protocol after searching.

Figure 2 is a flow diagram explaining the results of the search protocols, keywords and research questions.

We completed the PRISMA flow diagram to visually represent the flow of studies through the screening and selection process. After this, we include the number of records identified, screened, excluded, and included, along with the reasons for the exclusions.

Figure 2

Flow diagram of the PRISMA protocol



Findings from the VOSviewer Analysis

VOSviewer is a widely used software for visualizing and analyzing bibliometric networks, enabling researchers to uncover patterns and connections within extensive collections of scientific publications. This information typically includes details about the authors, publications, citations, and keywords. The software supports various file formats such as BibTeX, RIS, and plain text. For this article review, data were sourced from platforms such as Google Scholar, Scopus, and Web of Science.

The construction of bibliometric maps in VOSviewer relies on the VOS mapping technique (Van Eck & Waltman, 2010), where "VOS" signifies the visualization of similarities. While VOSviewer itself does not perform searches, users need to collect and import their search results into the software. Nonetheless, the techniques employed by VOSviewer are also used in other tools, and the insights it provides are invaluable for gaining a deeper understanding of research domains. This is particularly beneficial for researchers exploring new topics, such as Explorer. Within the program, users can select from various similarity-based options tailored to the dataset and the specific analysis required.

The keywords identified by VOSviewer are presented in Table 3.

Table 3
Keywords that VOSviewer identifies

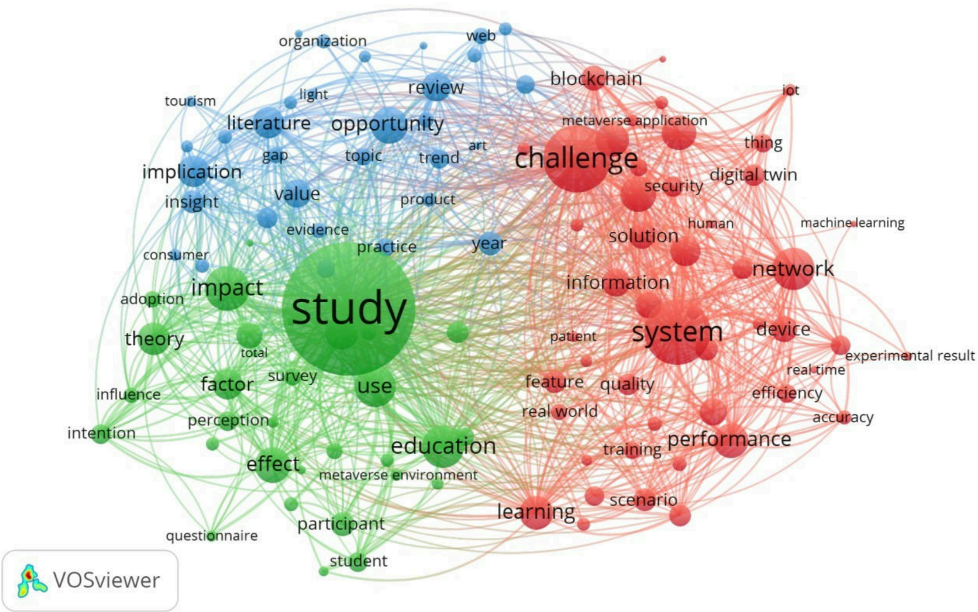
Id	Term	Occurrences	Relevance score
1	learning	26	1,6997
2	student	32	1,6225
3	education	32	1,3664
4	virtual reality	24	1,2557
5	experience	26	1,0869
6	study	27	1,0681
7	teaching	19	1,0298
8	article	10	0,9168
9	effectiveness	11	0,8526
10	technology	28	0,8277
11	immersive virtual reality	18	0,8245
12	use	16	0,7507
13	application	20	0,6396
14	research	17	0,6052
15	paper	21	0,4539

VOS aims to project all documents onto a two-dimensional chart, where the distance between them is inversely proportional to their similarity (i.e., more similar documents appear closer together).

The analysis of keywords identified by VOSviewer reveals that the literature on "Engineering Education Meets the Metaverse".is rich and varied, with a strong focus on student engagement, learning outcomes, and the integration of immersive technologies. The three clusters formed are shown by the visualization– Figure 3). The frequent occurrence of terms related to research and publications indicates an active and evolving field. This analysis can guide researchers and educators in identifying key areas for further study and in understanding the current trends and priorities in this interdisciplinary domain.

Overall, the keywords identified by VOSviewer provide a comprehensive view of the prominent themes and topics within the literature on engineering education and the metaverse. The analysis underscores the importance of learning methodologies, VR technologies, and educational research in shaping the future of engineering education within virtual environments.

Figure 3
Clusters represented with different colors



The Implications for Engineering Education and the Metaverse are as follows:

Student-Centric Approaches: The high occurrence of terms like 'student' and 'learning' suggests that the literature emphasizes student engagement and the impact of metaverse technologies on learning outcomes.

Technological Integration: The frequent mention of “virtual reality,” “immersive virtual reality,” and “technology” underscores the integration of advanced technologies in education and their role in transforming learning experiences.

Evaluating Impact: The terms “effectiveness” and “teaching” imply a critical examination of how these technologies affect teaching methodologies and their effectiveness in improving educational outcomes.

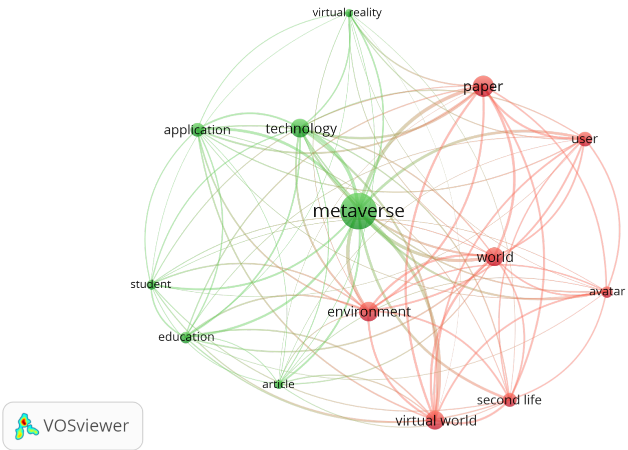
Research and Development: The presence of “study,” “research,” “article,” and “paper” highlights the research-intensive nature of this field, with ongoing studies contributing to a growing body of knowledge.

Practical Applications: The term “application” suggests a focus on how theoretical insights are being translated into practical educational tools and methods.

After new filtering, the terms are 5199, of which 23 meet the threshold. In the mapping, which was done according to the title, abstract and keywords in the publications, only those terms with a minimum of 25 occurrences were included. From them, 2 clusters were formed, represented in the two different colors in Figure 4.

After the analysis of titles and abstracts, 85 articles were analyzed according to their content.

Figure 4
Results from the last filtering



Discussion

RQ1: In what areas of engineering education is Metaverse learning practiced?

The Metaverse offers opportunities for immersive experiences, collaboration, and interaction, fostering the development of social experiences and enabling the emergence of "parallel worlds" (Schlemmer & Backes, 2015). According to Lee et al., 2021, developing the Metaverse involves three key stages: (1) Digital Twins: The creation of digital models and representations of the physical world, serving as virtual replicas of physical environments that operate synchronously; (2) Individuals with High Digital Competencies: The necessity for individuals to possess advanced technological skills to effectively manage and operate in digital environments; (3) Co-existence of Physical and Virtual Realities: Integrating and connecting the virtual and physical worlds into a seamless ecosystem.

Additionally, Davis et al. (2009) proposed a research model for the Metaverse, incorporating Virtual Reality elements, which includes the following: (1) the Metaverse itself, (2) users/avatars, (3) technological capabilities of the Metaverse, (4) behaviors, and (5) outcomes (Tlili et al., 2022).

In the realm of engineering education, Metaverse learning is applied across various fields, enhancing VR/AR-based content for three-dimensional object explanations and process visualizations. It is also employed in software engineering education (SEE) to improve learning outcomes and deliver immersive learning experiences.

However, Fernandes & Werner, 2022 highlighted a gap in the literature regarding the characterization of Metaverse applications in SEE. Figure 5 (De Felice et al., 2023) outlines the major educational subject areas benefiting from the Metaverse integration.

Research in WoS on the selected keywords indicates research interest in the following areas. The data in Table 4 cover the top 25 of all analyzed scientific fields.

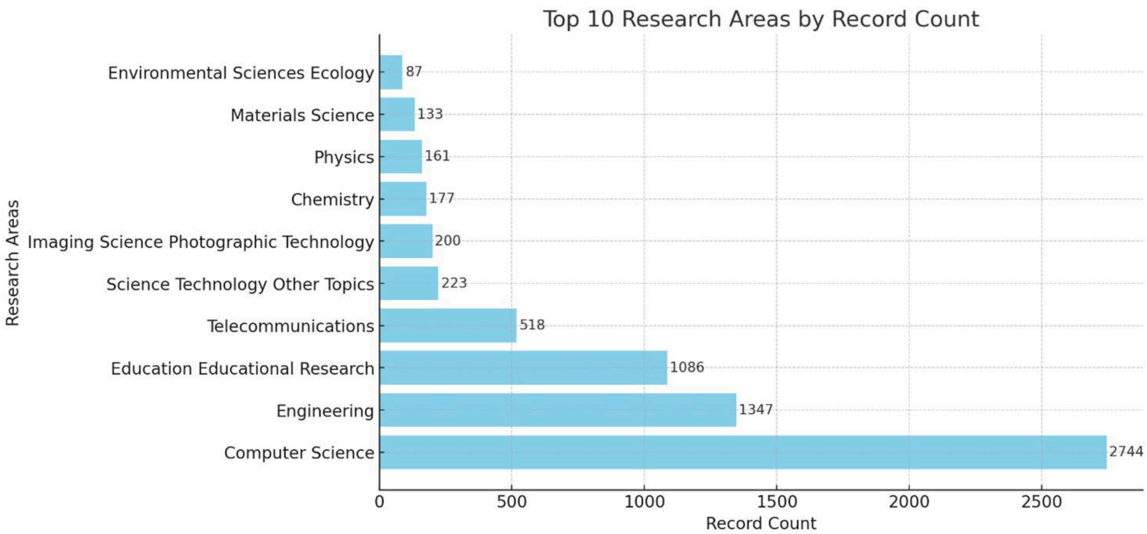
Table 4
Publications by Research Areas

Research Areas	Record Count	% of 4386
Computer Science	2744	62.563
Engineering	1347	30.711
Education Educational Research	1086	24.761
Telecommunications	518	11.810
Science Technology Other Topics	223	5.084
Imaging Science and Photographic Technology	200	4.560
Chemistry	177	4.036
Physics	161	3.671
Materials Science	133	3.032
Environmental Sciences and Ecology	87	1.984

Showing 10 of 70 entries

Figure 5

Research Areas in Engineering Education



The integration of the Metaverse in education is still limited, but its use in training engineers holds significant promise for preparing them for future digital transformations (Thongprasit & Piriyasurawong, 2022). To evaluate the impact and effectiveness of Metaverse-based training, it is essential to develop reliable instruments for assessing the educational experiences it offers (De Felice et al., 2023; Lopez-Belmonte et al., 2023). One notable limitation of adopting the Metaverse is the unequal access to high-speed internet and advanced hardware, potentially excluding certain populations from participation (De Felice et al., 2023).

Compared to traditional e-learning platforms like Moodle, Zoom, Google Classroom, and Meet, the Metaverse offers a distinct advantage by creating a sense of reality in virtual classes (Kanematsu et al., 2014). For engineering students, it provides more realistic simulation scenarios (Zaga, 2023). As an educational technology, the Metaverse has the potential to enhance student motivation and improve learning outcomes (Camilleri, 2023; Daz et al., 2020). Currently, the Metaverse is increasingly associated with education (Flores-Castañeda et al., 2024), although its applications extend successfully to fields like industrial automation, agriculture, healthcare, and more, with promising benefits for humanity in the years ahead (Zhou, 2022).

In engineering education, Metaverse learning spans several areas. One application involves using Metaverse platforms to enhance VR/AR-based content for explaining three-dimensional objects and visualizing object transformations (Lee & Lee, 2022). Another study focuses on integrating Metaverse platforms into engineering courses to boost motivation, encourage active learning, and deepen topic comprehension (Alvarez et al., 2023). In software engineering education, virtual worlds are employed to improve learning outcomes and offer immersive learning environments (Fernandes & Werner, 2023). Additionally, in computer science education, Metaverse technologies utilize VR and AI to create video recordings, personalized class notes, and virtual workspaces for students (Ho et al., 2023).

According to Daz et al., 2020, the potential impacts of incorporating the Metaverse in education include the following:

- **Enrichment and Transformation of Education:** Enhanced learning outcomes and increased student engagement and motivation (Camilleri, 2023; Flores-Castañeda et al., 2024; Zahra et al., 2021).
- **Creation of New Learning Environments:** Providing learners with access to parallel, safe, and personalized realities for education.
- **Elimination of Distance and Time Barriers:** Enabling remote and asynchronous learning opportunities.
- **Immersive and Interactive Experiences:** Improving the understanding and retention of knowledge through engaging experiences.
- **Facilitation of Collaborative Learning:** Promoting interaction among students and with digital objects.
- **Development of Digital Literacy:** Equipping students with the technological skills required for the future workforce.
- **Potential for Inclusive Education:** Accommodating various learning styles and needs through experiential, collaborative, cooperative, significant, explicit, and emotional learning approaches (Flores-Castañeda et al., 2024).
- **Opportunities for Interdisciplinary and Experiential Learning:** Bridging the gap between theoretical knowledge and practical application.
- **Cultural Exchange and Global Collaboration:** Connecting students from diverse countries and cultural backgrounds to foster mutual understanding.

The Metaverse can revolutionize the educational landscape (Locurcio, 2022).

Short summaries of the analyzed papers, including their focus, results, and conclusions, are presented in Table 5.

Table 5

A summary of some analyzed papers

Authors	Study focus	Results	Conclusion
Aşıksoy, 2023	This systematic review offers important insights for researchers and educators seeking to leverage the Metaverse in education.	The review emphasizes the need for additional empirical research on the use of mixed reality technology in educational metaverse environments, encouraging educators to explore its	The scarcity of experimental studies addressing students' behavioral engagement in metaverse-based education highlights a promising avenue for future research. By designing and implementing such studies, educators can

Authors	Study focus	Results	Conclusion
		potential for enriching student learning experiences.	explore how immersive virtual environment influence student engagement and develop targeted strategies to optimize learning outcomes.
Bradbury, 2022	This paper seeks to serve as a reference and source of inspiration for advancing the quality of vocational education in the Metaverse era.	The paper suggests that Metaverse technology can enhance vocational education by driving innovation and fostering the reform of teaching methods in vocational schools.	The paper emphasizes the importance of analyzing the potential risks associated with the Metaverse, including privacy, ethical, and addiction risks, and calls for the implementation of effective measures to mitigate these challenges.
Braguez et al., 2023	This review aims to define the Metaverse, outline the roles of augmented reality (AR), mixed reality (MR), and virtual reality (VR), and explore the concepts of digital twins and lifelogging.	The paper suggests incorporating the Metaverse into classroom settings as a complementary tool, rather than adopting it for full-time learning, ensuring its use is purposeful and enhances educational outcomes.	The significant potential of Metaverse technologies lies in their ability to provide immersive experiences, enriching both content engagement and social interactions.
Camilleri, 2023	This paper reviews how, why, where, and when Metaverse technologies can be utilized to enhance educational experiences and outcomes.	The Metaverse can facilitate the real-time learning of academic subjects through immersive virtual reality (VR) environments.	The Metaverse can serve as an educational technology that enhances student motivation and improves learning outcomes.
Chen & Liu, 2020	This study investigates how augmented reality (AR) can be applied in a chemistry course to enhance student engagement and improve learning outcomes.	The results indicate that integrating augmented reality (AR) technology into chemistry education can significantly enhance student engagement and improve learning outcomes.	The findings suggest that augmented reality (AR) can help students understand abstract concepts more effectively in chemistry education.
Chua & Yu, 2023	This study seeks to map trends in the educational use of the Metaverse and evaluate its perceived usefulness and ease of use from 2008 to 2022.	Perceived usefulness and perceived ease of use are crucial factors influencing the adoption of Metaverse technologies in education.	The study recommends future research to investigate the perceived usefulness and ease of use across diverse educational fields, incorporating various Metaverse platforms and devices into the research design.
De Felice et al., 2023	This review investigates the role of the Metaverse as an educational tool, exploring its potential to enhance learning experiences and engagement.	The research findings provide insights into the benefits, potential, and risks of the Metaverse as a tool for creating immersive and innovative learning experiences.	One major limitation identified is the absence of standardized assessment tools and metrics to effectively evaluate the impact and effectiveness of Metaverse-based education

Authors	Study focus	Results	Conclusion
			compared to traditional educational methods.
Mazzuco et al., 2022	A systematic literature review was conducted to understand the specific aspects of this context, particularly focusing on the main chemistry topics where augmented reality (AR) is applied.	Augmented reality enhances the understanding of complex chemistry concepts across different educational levels, making abstract and intricate topics more accessible and engaging for students.	The paper emphasizes the necessity for further research to bridge existing gaps and offers suggestions and directions to guide future studies in the field.
Roy et al., 2023	The study focuses on educational settings, emphasizing the significant impact that the metaverse system will have on teaching and learning environments.	This study outlines metaverse applications in education, highlights challenges, identifies adoption factors and themes, and suggests directions for future research.	The metaverse system benefits teaching and learning by enhancing engagement, enabling immersive experiences, facilitating real-time collaboration, and improving the understanding of complex concepts through interactive simulations.
Thongprasit & Piriyasurawong, 2022	The research focuses on developing a metaverse framework aimed at enhancing engineering competency through immersive, interactive, and collaborative virtual environments.	The metaverse framework for engineering competency development consists of three key components: Metaverse: The virtual environment where immersive and interactive learning takes place; Metaverse Platform: The technological infrastructure and tools that facilitate interaction, collaboration, and simulation; Engineering Competency for Future Readiness – The specific skills, knowledge, and abilities that the framework aims to develop to prepare students for future engineering challenges.	Training engineers through the metaverse is an effective approach to prepare them for the digital transformation of the future. The immersive, interactive, and collaborative nature of the metaverse allows engineers to develop practical skills, engage in virtual simulations, and adapt to emerging technologies, ensuring they are equipped to navigate the evolving digital landscape.
Zhonggen, 2023	This paper performed a systematic literature review to assess the acceptance of Metaverse technology in education over 16 years.	The study identified perceived usefulness and ease of use as the key factors influencing the acceptance or rejection of Metaverse technology in education.	Future research should investigate the perceived usefulness and ease of use across diverse educational fields, while also examining various Metaverse platforms and devices in their design.

RQ2. Which tools, technologies, or software platforms are employed in these practices?

A systematic review of 77 research articles (Flores-Castañeda et al., 2024) identified 14 emerging technologies shaping metaverse education, including artificial intelligence (AI), virtual reality (VR), 5G, EON-XR, digital twins (DT), 3D virtual reality, and immersive VR. These technologies contribute to real-world simulations within virtual environments (immersion), foster interaction with others (interactivity), enhance educational settings through innovative content delivery, and boost learning motivation by capturing student attention.

Recent advancements in metaverse-based education highlight the integration of VR, augmented reality (AR), and 3D simulations (Meena et al., 2023). The metaverse is expected to combine AR, VR, AI, and blockchain to create accurate and accessible virtual environments (De Felice et al., 2023). AI and IoT technologies underpin the development of digital virtual worlds in the metaverse, allowing students to engage in educational and social activities securely and dynamically (Mozumder et al., 2023).

The study underscored the role of 14 key technologies, including AI, VR, 5G, and DT, in promoting immersion, interactivity, and innovative content presentation, ultimately enhancing the educational landscape.

Virtual reality (VR)

Virtual reality (VR) aims to simulate realistic human environments by providing immersive, computer-generated 3D simulations that users can explore and interact with. This technology enables systems to detect user input and modify virtual worlds in real-time, fostering dynamic, interactive experiences. In education, VR helps address challenges in understanding complex objects, such as chemical compounds or anatomical structures, enhancing the learning process and improving efficiency (Petkov et al., 2019).

Platforms like Google Expeditions offer students with learning difficulties unrestricted participation in educational activities (Mitsea et al., 2023). VR environments and applications are specifically designed to enhance cognitive skills and provide immersive learning experiences for students with disabilities (Elfakki et al., 2023). By visualizing and interacting with material in a virtual setting, these students process information more effectively. VR games (VRGs) also support individuals with special educational needs and disabilities (SEND) by boosting motivation, fostering metacognitive skills, and promoting emotional intelligence (Prakash & Rajendran, 2023).

VR typically involves headsets or goggles that display virtual environments, alongside controllers or gloves for interaction, creating a sense of presence and immersion. Applications span entertainment, gaming, education, training, and simulation. Recent advancements in graphics, motion tracking, and haptic feedback have significantly enhanced VR experiences. Collaborative VR environments promote teamwork and communication by enabling students to interact and work on projects together (Petkov et al., 2019).

Due to their cost-effectiveness, VR technologies are widely adopted by universities, educational institutions, and industrial companies, offering practical alternatives to real-world scenarios (Novak-Marcincin et al., 2014).

Extended Reality (XR)

Extended reality (XR) is an umbrella term encompassing virtual environments, human-machine interactions, and wearable technologies. XR integrates virtual reality (VR) and augmented reality (AR), offering immersive experiences that merge the digital and physical worlds.

Augmented reality overlays computer-generated elements onto the real world, enhancing user perception and engagement across sectors such as gaming, retail, and education (Hayes, 2024). Mixed reality (MR) further blends physical and virtual environments, allowing users to interact with both simultaneously.

Table 6 outlines the key distinctions between AR, VR, MR, and XR, highlighting their unique applications and technological features.

Table 6

Comparison between Augmented Reality (AR) vs. Virtual Reality (VR) vs. Mixed Reality (MR) vs. Extended reality (XR)

Comparison	Virtual Reality	Augmented Reality	Mixed Reality	Extended reality (XR)
Definition:	Virtual Reality (VR), users are fully immersed in a digital environment, blocking out the real world and preventing direct interaction with their physical surroundings.	Augmented Reality (AR) overlays digital content or virtual objects onto the real world, enriching the user's experience by enhancing their perception and interaction with the physical environment.	Mixed Reality (MR) blends real and virtual environments, allowing physical and digital objects to co-exist and interact in real time. It integrates aspects of both Virtual Reality (VR) and Augmented Reality (AR) to create immersive and interactive experiences.	Extended Reality (XR) is an overarching term that includes all immersive technologies, such as Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). XR represents any technology that enhances or extends our perception of reality by blending digital and physical environments.
Scope:	Virtual Reality (VR) seeks to generate a feeling of presence and immersion, giving users the impression that they are physically situated within the virtual environment.	Unlike Virtual Reality (VR), Augmented Reality (AR) enables users to interact with and perceive both the real world and virtual elements simultaneously.	Mixed Reality (MR) integrates virtual and physical objects, enabling users to interact with both simultaneously. It offers a spectrum of experiences that range from fully virtual environments to entirely physical ones, blending digital content seamlessly with the real world.	Extended Reality (XR) covers a broad spectrum of immersive technologies, including Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). XR refers to any technology that modifies or enhances our perception of reality, regardless of how much the physical and virtual worlds are integrated.
Technology:	Virtual Reality (VR) is a computer-generated simulation of a 3D environment, allowing users to interact with it through specialized equipment like headsets, gloves, or controllers.	Augmented Reality (AR) is commonly experienced through devices such as smartphones, fitness trackers, tablets, or smart glasses. These devices use cameras and sensors to detect the real-world environment and overlay digital content onto it. AR technology can gather data on user health, activity levels, and surroundings, while also interacting with other devices to provide notifications, track fitness goals, or enable immersive AR experiences.	Mixed Reality (MR) relies on advanced sensors, cameras, and tracking systems to map the physical environment and overlay virtual objects onto it. Users are immersed in VR through technologies like VR head-mounted devices (HMDs) and high-degree-of-freedom tracking controllers. This technology demands a high level of spatial understanding and tracking capabilities to seamlessly integrate the real and virtual worlds.	Extended Reality (XR) encompasses various technologies. Virtual Reality (VR) generates a fully immersive digital environment, Augmented Reality (AR) overlays digital content onto the real world, and Mixed Reality (MR) blends elements of both to create an interactive mixed environment.
Applications:	Virtual Reality (VR) often demands significant computing power and is widely used in gaming, training, education, simulations, and virtual tours.	Augmented Reality (AR) is applied in diverse fields, including gaming, entertainment, education, and industrial training.	Mixed Reality (MR) is used across multiple sectors such as gaming, entertainment, education, and training. It enables users to engage with virtual objects within real-world environments, creating immersive and interactive experiences.	Extended Reality (XR) encompasses a broad spectrum of applications. Virtual Reality (VR) is commonly used in gaming, simulations, and virtual tours, while Augmented Reality (AR) is applied in education, healthcare, and industrial training. Mixed Reality (MR) merges elements of both VR and AR, enabling its use across diverse fields.

These technologies have been effectively integrated into manufacturing engineering education, offering students virtual environments to develop and refine their skills (Novak-Marcincin et al., 2014). Unlike virtual reality (VR), which constructs an entirely digital environment, augmented reality (AR) enhances the real world by overlaying additional content and information (Hayes, 2024). VR enables users to interact with digital objects and other participants in ways that feel lifelike, while AR uses devices such as smartphones, tablets, or headsets to introduce virtual elements into real-world scenarios.

Mixed reality (MR) merges physical and virtual environments by leveraging advanced computing, imaging, and input technologies. Devices like Microsoft HoloLens incorporate sophisticated sensors and cameras to track user movements and place virtual objects accurately within the real world. This interaction allows users to engage with virtual objects as if they existed physically, fostering highly immersive experiences. MR finds applications in fields such as architecture, design, and engineering, where it is used to visualize and manipulate 3D models. The term extended reality (XR) encompasses all immersive technologies, including VR, AR, and MR, and is frequently referenced in academic and research settings.

In XR, VR immerses users in a fully digital environment, AR overlays virtual components on the physical world, and MR blends the two seamlessly, allowing users to interact with virtual objects in real-time environments.

Augmented reality (AR) is increasingly utilized in chemistry education, serving as a valuable pedagogical tool for understanding complex scientific concepts (Mazzuco et al., 2022; Saidin et al., 2016). Hands-on AR applications have demonstrated potential in motivating students and sustaining long-term engagement. Research indicates that students using AR for chemistry experiments achieved greater conceptual understanding and higher engagement levels compared to those taught through conventional methods (Chen & Liu, 2020). AR enhanced the learning experience by enabling students to visualize and manipulate chemical elements in virtual environments, facilitating the comprehension of abstract ideas. This approach resulted in improved learning outcomes and increased student interest (Chen & Liu, 2020).

AR technologies also boosted student motivation, promoted teamwork, and contributed to lasting knowledge retention (Muhammad et al., 2021). Both AR and VR are applied across STEAM disciplines (Science, Technology, Engineering, Arts, and Mathematics) without differentiation between subjects in metaverse-based education (Braguez et al., 2023; Kanematsu et al., 2014). AR-supported flipped learning strategies not only enhanced students' project performance but also fostered greater learning motivation, critical thinking, and collective self-efficacy within groups (Chang & Hwang, 2018). Findings revealed that students expressed satisfaction with AR experiences and expressed interest in continuing to use such applications in the future (Sahin & Yilmaz, 2020).

Internet of Things

The Internet of Things (IoT) refers to a network connecting physical objects, known as “things,” embedded with sensors, communication tools, and networking technologies. These objects exchange data, information, and knowledge with other devices and systems through existing network infrastructures (Zhou, 2022). IoT devices facilitate data transfer between computers and humans across networks. IoT is seen as a transformative force in education, with the potential to enhance learning outcomes, boost operational efficiency, and improve student performance (Sailesh, 2023).

Digital technologies in education aim not only to expand accessibility but also to improve the efficiency and inclusivity of traditional educational systems. IoT is reshaping education by fostering interactivity, collaboration, and inclusivity (Ingole, 2022; Kalid et al., 2022; Rodrigues, 2023). Through IoT devices, teachers can track real-time data on student progress, enabling more accurate assessments of academic performance (Ingole, 2022).

Smart boards function similarly to traditional blackboards but can also display visuals and images relevant to the topic. IoT innovations, such as GPS-equipped school buses, smart security cameras, and tablets with educational applications, are transforming how educational institutions operate. Daily concerns like student attendance can also be managed more effectively with IoT.

The IoT will enhance operational efficiency across diverse learning environments. IoT in classrooms can refine lesson planning, improve learning resources, enrich teaching methods, optimize administrative functions, and reduce operational costs (Sailesh, 2023). In academic contexts, IoT sensors gather data and suggest relevant academic topics for students, guiding their future learning paths.

RQ3. What teaching strategies or educational frameworks are used in this context?

A metaverse framework for developing engineering competencies includes three elements: the metaverse itself, the metaverse platform, and the competencies required for future readiness (Thongprasit & Piriyasurawong, 2022). In the metaverse, students engage with digital content and their peers in immersive and interactive environments. They participate in virtual simulations, role-playing scenarios, and collaborative global projects (Abraham et al., 2023).

The proposed metaverse education system integrates virtual reality (VR) and blockchain technologies to foster social learning. Learners collaborate to deepen their knowledge, while the blockchain ensures secure and equitable tracking of progress and grading (Zheng et al., 2023).

The pedagogical framework for metaverse education is grounded in constructivist principles, emphasizing active participation, experimentation, and exploration. The essential elements include immersive simulations, XR-based student engagement, and social learning facilitated through avatars.

Principles for developing the framework of training in edu-metaverse

The framework for training in the edu-metaverse, as outlined in (Sin et al., 2023) and supported by references (Honebein, 1996) and (Murphy, 1997), is based on several core principles:

- P1: Facilitate Knowledge Construction Experiences–Learners must recognize that knowledge is a constructed representation of the world.
- P2: Integrate Relevance into Learning–New learning should be connected to prior knowledge to enhance understanding.
- P3: Promote Exposure to Multiple Solutions–Providing learners with diverse perspectives fosters a deeper and more comprehensive grasp of concepts.
- P4: Embed Learning in Realistic Contexts: Associating knowledge with real-world applications enhances engagement and reinforces relevance.
- P5: Foster Ownership of Learning–Encouraging students to independently seek out knowledge broadens their learning experiences.
- P6: Use Multiple Representations–Presenting information through different formats helps learners form a well-rounded understanding of concepts.
- P7: Promote Exploration: Learners should be encouraged to pursue knowledge independently, fostering curiosity and discovery.
- P8: Encourage Social Learning–Collaborative learning environments enable learners to refine their understanding by engaging with peers.

These principles align with the constructivist framework, which posits that knowledge is internally constructed through active engagement with new concepts. Learning occurs not by passively receiving information but through exploration and interaction (Sin et al., 2023).

Traditional teaching methods often emphasize memorization and passive learning, whereas constructivist approaches prioritize active participation, experimentation, and the discovery of cause-and-effect relationships. Constructivist teaching cultivates students' cognitive, emotional, psychomotor, and experiential abilities (Mijanović, 2023).

Metaverse Learning Principles:

The metaverse learning principles center around crafting immersive, interactive educational experiences through virtual environments. These principles emphasize collaborative and project-based learning to deliver instructional content and achieve educational goals (Lopez-Belmonte et al., 2023). The design of metaverse spaces is pivotal in fostering interaction among students and enhancing their overall learning capabilities (Ahn & Heo, 2023). Similar to online learning, metaverse-based education promotes self-directed learning, collaboration, and experiential learning; however, it assumes a fundamentally altered sense of reality within the metaverse (Dreamson & Park, 2023). This approach allows learners to engage with digital content, participate in virtual simulations, role-playing exercises, and collaborative projects, while also accessing diverse resources within a single platform (Sabarinath, 2023). Multiple models and frameworks have been developed to facilitate the integration of the metaverse into educational settings.

A defining feature of metaverse learning is Immersive Learning (IL), which takes place within extended reality (XR). XR's primary draw is its ability to create a heightened sense of presence, or the feeling of "being" in a virtual environment (Gibson, 2014). Additionally, immersion through IL helps students concentrate on mastering the educational material rather than navigating the user interfaces (Sin et al., 2023).

The key metaverse learning models include:

- (M1) Visualizing Knowledge as Constructs: Knowledge is seen as an internal construct requiring mental organization. Students must understand knowledge to actively engage with its formation (P1).
- (M2) Knowledge Association: New concepts are grasped through connections to the learner's prior knowledge (P2).
- (M3) Immersive Simulations: Knowledge serves to model reality. Students benefit from exploring problems from various perspectives to develop comprehensive internal models (P3).
- (M4) Real-World Problem Reenactment: Daily experiences form the basis for new learning. IL supports situated learning by reenacting real-life problems, allowing students to relate problem-solving processes to real-world contexts (P4).
- (M5) XR Student Engagement: Students take responsibility for their learning journeys (P5).
- (M6) Multimodal Content Delivery: Presenting content through different modalities enhances the construction of robust mental models (P6).
- (M7) Knowledge Exploration: Interactive experiences play a crucial role in synthesizing new knowledge (P7).
- (M8) Social Learning with Avatars: Collaborative learning environments enable students with diverse experiences to guide and challenge each other (P8).

A pedagogical framework for metaverse-based training has been proposed by (Sin et al., 2023), highlighting the following:

1. A ubiquitous platform for exploring interconnected educational concepts.
2. Intuitive interaction grounded in physical metaphors.
3. Integration with real-world learning through the advantages of digital content.

The central idea behind edu-metaverse frameworks is to merge the structure of knowledge graphs (KG) with VR immersion, enabling deeper exploration of educational content.

RQ4. How do collaboration and interaction between humans and computers occur within the Metaverse?

Metaverse collaboration allows multiple users to engage, communicate, and interact within virtual environments. This can involve activities such as virtual meetings, shared workspaces, gaming, and social interactions. The metaverse acts as a digital platform that connects individuals regardless of their physical location.

Version 2 (V2) of metaverse collaboration emphasizes virtual environments that facilitate communication and interaction, enhancing user engagement and fostering teamwork. Human-computer interaction (HCI) in the metaverse focuses on designing immersive and intuitive interfaces to improve user experience.

HCI is a multidisciplinary field dedicated to understanding, designing, and evaluating the interactions between humans and computers (Haux, 2023). It seeks to create user-friendly interfaces, efficient, and intuitive, drawing from fields such as anthropology and sociology (Wardhani, 2023). Methods within HCI include ethnography, participatory design, controlled experiments, and usability testing (Martínez-Miranda & Pérez-Espinosa, 2023). HCI research extends into various aspects of life, including spirituality, accessibility for individuals with disabilities, and emerging technologies like virtual reality and wearable devices (Jyoti & Kaur, 2023). The discipline has evolved from developing basic user interfaces to creating complex interactive systems capable of recognizing and simulating human emotions (Meen Teen-Hang & Tijus, 2023). HCI aims to enhance human-computer interaction by making technology more usable and accessible, integrating knowledge from design, psychology, ergonomics, and computer science.

The convergence of metaverse collaboration and HCI focuses on developing and studying interaction techniques and user interfaces within virtual environments. This involves analyzing how users engage with virtual worlds and one another, with an emphasis on creating interfaces that enable seamless communication and teamwork.

The field explores methods to improve usability, elevate user experience, and craft immersive digital spaces. Social and psychological dimensions—such as presence, identity, and social norms—are also considered when developing HCI for the metaverse.

Fang, 2022 outlines four key HCI frameworks:

1. A generic computing model for HCI;
2. A touchscreen display control model for the HCI;
3. An immersive virtual reality HCI model;
4. A metaverse-specific HCI model.

RQ5: What is the role of digital twins in Metaverse education?

Digital twins are virtual representations of physical objects or systems, created using data and simulations to enable real-time monitoring, optimization, control, and decision-making. They have garnered significant interest across industries for their capacity to enhance efficiency and inform better decisions (Ferrigno, 2023; Fuller, Fan, & Day, 2020). The concept of “digital twins” originated from NASA’s Apollo program, where two identical spacecraft were constructed to replicate conditions during space missions. The vehicle that remained on Earth was referred to as the “twin” (Cellina et al., 2023). Michael Grieves was the first to formally introduce the idea of a Digital Twin (DT) (Babbar, 2023).

By replicating physical systems, digital twins facilitate real-time simulations, optimizations, and predictive insights, contributing to more informed decision-making processes. These models are increasingly vital in education, offering realistic simulations that help simplify complex subjects and improve learning outcomes. Throughout a product's lifecycle, digital twins assist in simulating, predicting, and refining both the product and its manufacturing systems before committing to real prototypes and physical assets.

In sectors such as oil and gas, digital twins enhance asset management, operational efficiency, and simulate the performance of new infrastructure (Kortelainen, Minav, & Tammi, 2023). In healthcare, digital human twins (DHTs) replicate patient data, advancing personalized and data-driven treatments (Babbar, 2023). In educational contexts, DTs can provide teachers with insights into students' academic and behavioral patterns, allowing for tailored support to address learning difficulties. Students with special needs can engage in simulated scenarios, preparing them for real-world challenges. Integrating digital twins with virtual reality (VR) offers further support for overcoming learning barriers.

Digital twins also play a role in vehicular networks by improving resource allocation and edge computing efficiency (Losovsky, 2023). The evolution of digital twins has accelerated with advancements in artificial intelligence, data analytics, and the Internet of Things (IoT) (Cali et al., 2023; El-Din, El-Shafai, & El Sayed, 2023; Ferrigno, 2023; Jadhav & Sarnikar, 2023). Their application spans industries such as construction, healthcare, manufacturing, oil and gas, and smart cities (Saha, Banik, & Banik, 2023). For example, Singapore has adopted digital twin models to predict and simulate disaster scenarios, using IoT data and satellite imagery to monitor infrastructure and enhance response strategies (Maiti & Kayal, 2024).

Despite their promise, the widespread adoption of digital twins faces challenges, including concerns related to data security, quality, and interoperability. Addressing these issues will be critical for their continued growth and integration.

Conclusion

Education in the Metaverse remains in its infancy, with efforts focused on concept development, experimental testing, and discussions among educators, researchers, and technology stakeholders. The concept development stage involves developing and refining frameworks to deliver and experience education in virtual reality. This includes exploring potential applications, understanding associated challenges, and envisioning how such environments can complement or transform traditional education systems.

Pilot studies and experiments play a critical role in evaluating VR-based learning. These initiatives involve designing specific educational interventions, assessing learner engagement, and analyzing outcomes to identify strengths and limitations. Insights gained from these experiments inform best practices and guide the optimization of Metaverse-based education.

The current findings emphasize the Metaverse's potential to create immersive, interactive, and collaborative learning experiences, enabling personalized and engaging education. However, challenges such as technological barriers, access inequality, and the need for effective pedagogical strategies must be addressed.

Future implications for the field include the following:

- Improving Accessibility: Developing cost-effective technologies and addressing infrastructure limitations to ensure equitable access.

- Refining Pedagogical Models: Creating adaptable and interdisciplinary teaching frameworks to leverage the Metaverse's unique capabilities.
- Fostering Collaboration: Encouraging partnerships among educators, technologists, and policymakers to design inclusive and scalable solutions.
- Evaluating Long-term Impact: Conducting longitudinal studies to measure the effectiveness of Metaverse education on learning outcomes, skill development, and workforce readiness.

While the Metaverse holds promise to revolutionize education, its successful integration requires further research, innovation, and collaboration to overcome current limitations and unlock its full potential.

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