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# Extended reality for education: Mapping current trends, challenges, and applications

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**Abstract:** The advancements in 5G technology and Artificial Intelligence (AI) have accelerated the integration of immersive technologies such as Extended Reality (XR) into educational practices. There is a notable scarcity of studies focusing specifically on the applications and impact of XR in academic settings. Most existing research has concentrated on AR and VR, leaving a gap in understanding the full potential of XR. Addressing these gaps and challenges is crucial for harnessing the full potential of XR in education. This study aims to map and analyze the applications, trends, and educational challenges of XR technology. This study conducts a bibliometric analysis covering XR's application in education from 2018 to 2023, analyzing 32 articles from Scopus sources. Key findings highlight XR's annual growth in research publications, with significant contributions from the United States, China, and Canada. XR enriches education by facilitating immersive simulations, real time interaction with virtual objects, and spatial manipulation in three dimensions. It fosters presence and embodiment in virtual environments, supports practical training through realistic simulations, enhances multi-sensory engagement, promotes collaborative learning environments, and improves accessibility for diverse learners. The main challenges of XR technology include high costs, technical hurdles, regulatory issues, infrastructure limitations, and the need for digital literacy and skills. Addressing these challenges, collaborative efforts among educators, researchers, and industry stakeholders are required. Such collaboration is crucial for harnessing the full potential of XR technology to revolutionize education and prepare learners for a dynamic future.

**Keywords:** Extended reality; Quality education; Educational technology; Media technology; Systematic literature review



## 1. Introduction

The ever-evolving world of technology continually offers various advanced benefits (Almgren & Skobelev, 2020; Prasetya et al., 2023; Skare & Riberio Soriano, 2021). The 2030 Agenda for

Sustainable Development underscores Goal 4, which emphasizes ensuring inclusive and equitable quality education (Kioupi & Voulvoulis, 2022), and promoting lifelong learning opportunities for all (Toit-brits, 2019). As a global priority, the integration of digital technology in education has emerged as a crucial factor, reinforcing the notion that digitization remains, and will continue to be, one of the primary drivers of educational progress (Samala, Marta, et al., 2022; Samala, Ranuharja, et al., 2022). The emphasis on digitalization highlights its transformative potential in education, paving the way for innovative approaches and inclusive learning environments.

Technology significantly influences education (Muskhir et al., 2023; Samala, Dewi, et al., 2023). To achieve sustainable development in education, technology must motivate educators to explore and employ new methods and practices, thereby enhancing the quality and efficacy of education (Rauschnabel et al., 2022). One of technological advancements is Extended Reality (XR). XR represents an innovative convergence of these technologies (Khlaif et al., 2024). It serves as a comprehensive framework for immersive experiences that blend the physical and virtual realms (Rauschnabel et al., 2017). This unique capacity allows individuals to traverse virtual worlds while remaining rooted in their physical surroundings, even from their homes. Essentially, XR acts as a holistic container encompassing VR, AR, and MR, propelling the concept of blended realities to new heights (Prasetya et al., 2024; Samala, Govender, et al., 2024; Waskito et al., 2024). The developmental potential of XR is consistently expanding and is making its presence felt across numerous sectors, including education.

In the landscape of education, while extensive study has explored the applications of AR and VR, studies focusing on XR remain relatively scarce. This limitation is primarily due to XR's status as an emerging technology with vast potential in uncharted territories. The use of bibliometric analysis in this research serves several critical purposes. Firstly, it maps the adoption trends of XR in education, complementing traditional literature reviews by providing quantitative and qualitative insights into XR study. Secondly, bibliometric methods facilitate a comprehensive exploration of specific study domains by constructing scientific network maps highlighting popular areas and emerging themes in XR-based education. This approach illuminates XR's development within the academic sphere, provides valuable insights for policy development, and guides future research directions in education (Linnenluecke et al., 2020).

A high-quality systematic literature review can provide a strong foundation for research, ensuring the accuracy and relevance of the findings. One approach that can be used is bibliometrics. Bibliometrics uses data or bibliographic information related to scientific publications to identify trends, patterns, and developments in specific research areas (Delesposte et al., 2021; Hassan & Duarte, 2024). In other words, bibliometrics can enhance the quality of research outcomes, expand the understanding of specific topics, and identify research gaps that need to be addressed, such as the practical applications of XR in education, its long-term impacts, and its pedagogical effectiveness (Samala, Usmeldi, Taali, Ambiyar, et al., 2023)

This study aims to identify and analyze the diverse applications of XR technology in higher education, enabling educators and institutions to explore novel approaches for integrating XR into teaching and learning processes to potentially enhance student engagement and learning outcomes. By advancing the use of XR in education, this study seeks to inspire further innovations and foster productive collaborations between researchers and technology developers, ultimately enhancing XR applications to achieve educational goals. The study focuses on addressing the following questions:

RQ1. What are the publication and citation trends of XR in education?

RQ2. Who are the leading countries with the most publications of XR in education?
RQ3. In which disciplines has XR technology been applied?
RQ4. What are the current trending topics and challenges of XR in education?

### *XR: VR, AR, MR—What's the Difference?*

AR is a technology that adds to, or augments, physical surroundings with digital content, such as images, sounds, or information (Fortuna et al., 2024; Samala & Amanda, 2023). VR is a technology that immerses users in a virtual environment different from their physical surroundings (Craig et al., 2009). MR is a technology that combines VR and AR elements to create a hybrid environment where virtual and physical objects can interact (Bai et al., 2021). XR is a catch-all term that covers VR, AR, MR, and other forms of immersive media—digital content presented to users from a first-person perspective. Extended reality (XR) is an umbrella term encompassing any technology that alters reality by adding digital elements to the physical or real-world environment to any extent, blurring the line between the physical and digital worlds.

To better understand the differences between the three concepts as depicted in Figure 1. The virtuality continuum—the critical word—contains the full spectrum of possibilities between the entirely physical or real environment and the fully digital or virtual environment (Gittens, 2024; Valente et al., 2018). In a continuum, adjacent parts are almost indistinguishable, but the extremes differ. Paul Milgram and Fumio Kishino introduced the concept of the virtuality or reality-virtuality continuum in 1994 (Skarbez et al., 2021). The virtuality continuum is a theoretical framework that helps researchers visualize and comprehend the distinctions between current technologies and those yet to be invented (Heemsbergen et al., 2021). However, at times, the exact boundaries of these technologies may not be entirely clear, and there may be overlapping characteristics.

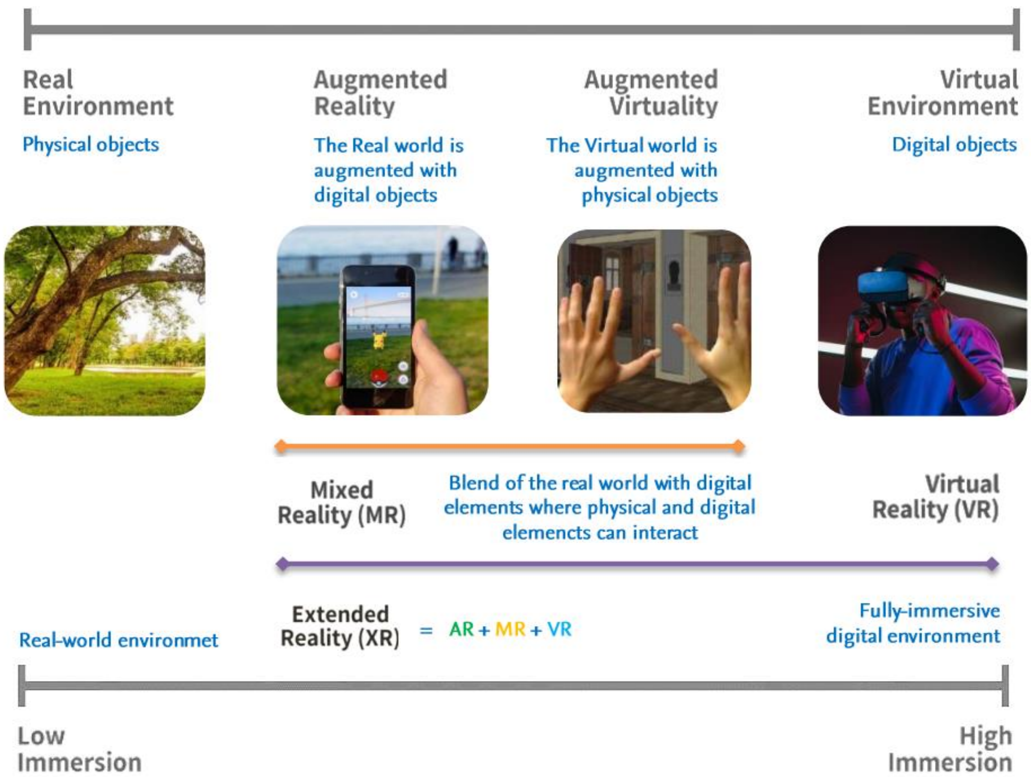


Figure 1. The virtuality continuum

Based on Figure 1, a more specific definition can be elucidated as follows:

- **AR** technology enables the superimposition of digital elements into the real-world environment. In AR experiences, users perceive a composite view incorporating physical, real-world, and digital components (Dini & Mura, 2015; Eder et al., 2020).
- **VR** is a technology that facilitates the creation of fully-immersive digital environment. In VR experiences, users experience complete immersion in a digitally simulated environment, and the physical or real-world environment is entirely blocked out (Muskhir et al., 2024; Nee & Ong, 2013).
- **MR** is a technology that superimposes digital elements into the real-world environment and enables their interaction with the physical surroundings. MR experiences seamlessly integrate digital content with the real-world environment, allowing for immersive and interactive experiences (Samala, Usmeldi, Taali, Daineko, et al., 2023).
- **XR** is an umbrella term that encompasses all these different technologies, including AR, MR, and VR. XR represents the collective spectrum of technologies that bridge the divide between the physical and digital realms, offering a range of immersive experiences (Alhakamy, 2024; Jauhiainen, 2024).

Immersive technology expands reality by enhancing users' views of the real world without replacing it – known as augmented reality (AR) (Ruiz-Ariza et al., 2018). The mobile game Pokémon Go allows players to point their smartphone cameras at real-world locations and interact with virtual characters that appear as if they are there (Apperley & Moore, 2019). On the other hand, technology completely blocks users' view of the real world and replaces it with a computer-generated environment – we call this virtual reality (VR) (Samala, Ricci, et al., 2024). A blend of AR and VR is known as mixed reality (MR) (Flavián et al., 2019). MR can provide augmented experiences using VR headsets (Alcañiz et al., 2019). An MR application could enable students to learn about the solar system together in class as if the planets were floating right in front of them (Babalola et al., 2023). By pressing a button, students can view simulations of how the solar system operates (Chen et al., 2022; Khlaif et al., 2024).

Furthermore, XR follows in the footsteps of previous technologies that have made incremental progress in conveying increasingly complex information to users. XR enables interactions modeled on how we naturally interact with the real world (Le Noury et al., 2022). Immersive technologies like XR expand reality by seamlessly integrating information into users' perception of the world – whether it's the real world, a fully replaced virtual world, or a blend of both (Onu et al., 2024). Unlike usual teaching methods that use technology where interactions with information are perceived as external and separate, such as the use of physical textbooks and overhead projectors, modern approaches integrate technology seamlessly into the learning process, making it an integral part of the students' academic experience. XR transcends awareness to enhance immersive experiences – making it feel as if these elements are present among us (Newton et al., 2024). As an example, in a boxing game on a computer, users sense the swing of punches, the feeling of being in the ring, the impact of getting hit, and seeing opponents right in front of them. With XR, one can virtually travel back in time, wearing an XR headset to learn about extinct animals and plants, getting up close to feel their size, shape, and presence in the world (Pringle et al., 2022).

XR technology indeed possesses a remarkable capability to construct realistic and sensible simulations that allow users to interact directly with 3D content (Zhang et al., 2023). The level of immersive sensation depends significantly on the sophistication of the devices and the maturity of the technology (Memarian & Doleck, 2024). Specifically, XR technology offers valuable alternative solutions for learning scenarios that are dangerous, impossible, expensive, or rare, such as firefighting training, flight simulations, medical operations, and geographical studies (Berthiaume et al., 2024; Buhalis et al., 2023; Çöltekin, Griffin, et al., 2020; Ross & Gilbey, 2023). XR's ability to replicate these environments not only helps reduce costs associated with conventional training but also enhances safety by enabling learners to confront these situations in controlled and safe environments (Xu et al., 2023).

In the context of education, XR can support various simulations in learning (Herur-Raman et al., 2021). With XR, students can conduct laboratory experiments without the need for disposable materials that often need frequent replacement (Pyun et al., 2022). For example, in chemistry labs, students can manipulate chemical substances and laboratory equipment virtually (Zhou et al., 2024), reducing costs and the risk of accidents associated with actual chemicals (Kumar et al., 2021). Engineering students can learn to operate machinery and heavy equipment through XR simulations. For instance, they can study how to assemble and repair machines without requiring physical access to expensive and hard-to-reach equipment (Curran et al., 2023; Estrada et al., 2024; Guo et al., 2021).

Students can explore different ecosystems or natural phenomena such as volcanoes (Li, 2023), deep seas, or outer space through XR (Çöltekin, Lochhead, et al., 2020; Huerta-Cancino & Alé-Silva, 2024), providing them with deep and realistic experiences of concepts that are difficult to explain through text and images alone (Theodoropoulou et al., 2020). XR can create immersive environments where students can practice foreign languages. For example, they can interact with virtual native speakers in environments similar to the target language's country, enhancing conversation skills and cultural understanding (Yudintseva, 2023).

Students can "visit" historical places and witness historical events as if they were there, helping them understand the context and significance of historical events in a more engaging manner (Innocente et al., 2023). The presence of XR further reinforces the emergence of a connected ecosystem in the future where everyone can work, play, learn, shop, and interact in rich and realistic virtual environments (Cho & Park, 2023; Kee et al., 2024). This ecosystem is often referred to as the Metaverse (Tukur et al., 2024).

In 2023, the metaverse emerged as a highly trending topic in the current technological landscape (Buhalis et al., 2023; Dwivedi et al., 2022; Peukert et al., 2024; Tlili et al., 2022). The term metaverse refers to a virtual shared space where users can interact with each other and digital content in real time, blurring the boundaries between physical and virtual realities (Andriani et al., 2024; Samala, Usmeldi, Taali, Ambiyar, et al., 2023). The metaverse ecosystem extends beyond mere interaction media; it represents a new world blending creativity, futurism, and imagination akin to a gaming world (referred to as Surreality) (Bojic, 2022). Surreality denotes a state where physical and virtual worlds overlap and integrate deeply, creating immersive experiences enriched with imaginative visual elements that blur the boundaries between reality and virtuality. This concept explores the potential to create intense experiences where individuals can engage in activities and interactions that surpass the constraints of traditional physical reality. Within this realm, one can envision mythical creatures like fairies from Greek mythology, perform feats deemed impossible and illogical in the real world (such as flying and casting spells like in Harry Potter), albeit limited to audiovisual sensations within the confines of virtual reality as depicted in Figure 2.

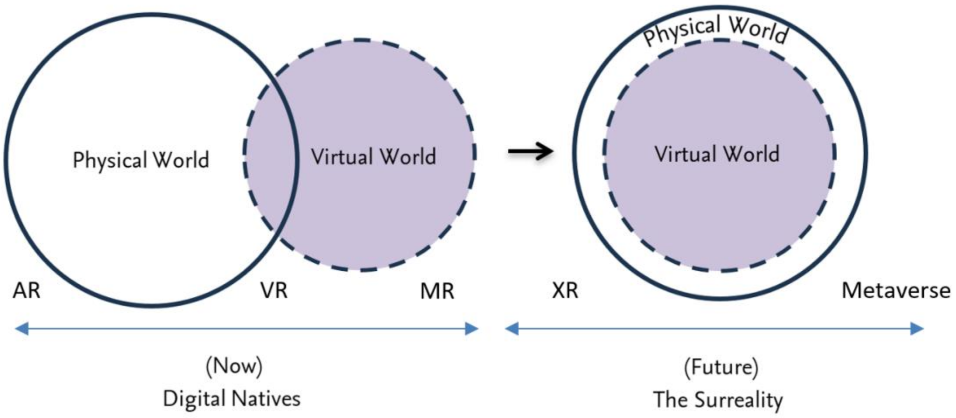


Figure 2. Metaverse: Now and future

The metaverse encompasses a broader scope than XR technology, as various technologies integrate into a decentralized virtual world built on a blockchain network (Bojic, 2022). In this virtual realm, every individual possesses an avatar and attributes (digital collections), engaging in activities similar to those in the real world, encompassing social and economic transactions, cultural experiences, entertainment activities, and more, facilitated by artificial intelligence (AI), Web 3.0, non-fungible tokens (NFTs), and digital payment methods such as cryptocurrencies like Bitcoin (BTC), and Ethereum (ETH) (Belk et al., 2022; Huynh-The et al., 2023; Vidal-Tomás, 2022). For example, in the metaverse, users can interact with others through their avatars, engage in economic transactions such as trading virtual goods using NFTs, attend cultural or entertainment events like virtual concerts, and even participate in simulations or experiments that are difficult to conduct physically (Guan et al., 2024). All these activities are enriched by AI technology that enables more natural and adaptive interactions and digital payment systems that facilitate transactions within this virtual environment as depicted in Figure 3.

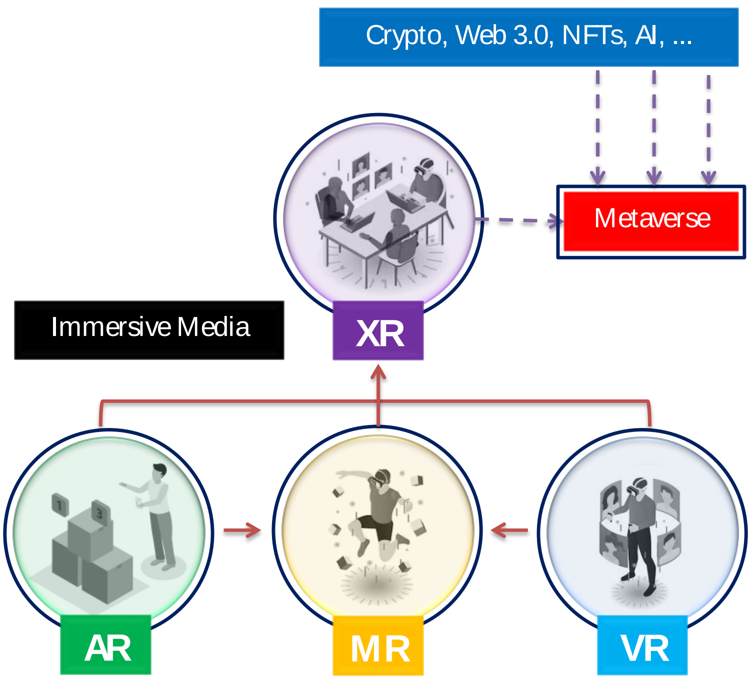


Figure 3. VR, AR, MR, XR, and metaverse

As XR technology advances, significant innovations with the potential to transform the world are expected. This technology will play a pivotal role in reshaping education, addressing the challenges faced by schools, teachers, and students.

## 2. Methods

This study aims to systematically review the literature on utilizing XR technologies in education. A systematic review comprehensively evaluates a clearly defined research problem and employs rigorous and transparent methods to identify, select, and critically appraise relevant studies (Page et al., 2021). It involves collecting and analyzing data from the included studies to address the research questions formulated beforehand (Moher et al., 2009). To ensure methodological rigor, the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) approach was choosen, which provides guidelines for transparent reporting in this review.

The choice of the PRISMA approach within this methodological framework is essential to ensure a systematic and transparent synthesis of research findings related to XR in education. PRISMA guidelines enhance the rigor of systematsic reviews by standardizing data collection, analysis, and reporting processes. This approach aims to improve the reproducibility and reliability of synthesizing scholarly literature on XR applications, specifically in education contexts (Page et al., 2021).

The review process comprised three main steps (Figure 4): (1) searching and collecting relevant data, (2) screening and assessing the eligibility of studies, and (3) analyzing the selected studies. The analysis employed bibliometric methods to gain insights into the included studies' publication patterns, authorship, citation networks, and other bibliographic characteristics.

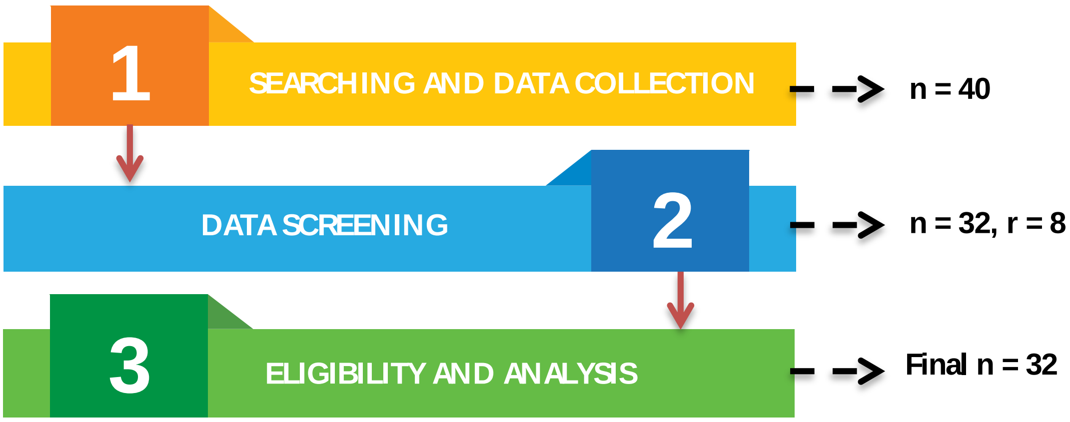


Figure 4. Systematic review procedure (adopted PRISMA)

The study utilized several tools, including R Studio, Python, VOSviewer, and MS Excel, to facilitate data analysis and visualization in this study. This combination of tools enabled the generation of rich, easily interpretable, and visually appealing visualizations to illustrate the findings effectively (Donthu et al., 2021).

### *Search and data collection*

The data collection are from Scopus database, due to for its reputable status in academic research (Pranckutė, 2021). The search took place on July 4, 2023. During the investigation, only the

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title, abstract, or keywords of the articles were used for data retrieval. The following query was employed to retrieve relevant data:

TITLE-ABS-KEY ( ("XR" OR "Extended Reality") AND "Education" ) AND DOCTYPE ( "cp" OR "ar" ) AND LANGUAGE ( "English" ) AND PUBYEAR > 2017 AND PUBYEAR < 2024

A total of 40 articles were successfully identified. All articles were restricted to those written in English, with a publication year limit ranging from 2018 to 2023. The keyword criteria included "Extended Reality," or "XR," and "Education." Only journal articles and conference papers were selected during the review process, while other document types such as book chapters, editorials, and books were excluded. The completeness of bibliographic metadata results is presented in Table 1, and the main information from the dataset obtained is depicted in Figure 5.

Table 1. Completeness of bibliographic metadata

| Metadata | Description | Missing counts | Missing % | Status |
|---|---|---|---|---|
| AB | Abstract | 0 | 0.00 | Excellent |
| C1 | Affiliation | 0 | 0.00 | Excellent |
| AU | Author | 0 | 0.00 | Excellent |
| DT | Document Type | 0 | 0.00 | Excellent |
| SO | Journal | 0 | 0.00 | Excellent |
| LA | Language | 0 | 0.00 | Excellent |
| PY | Publication Year | 0 | 0.00 | Excellent |
| TI | Title | 0 | 0.00 | Excellent |
| TC | Total Citation | 0 | 0.00 | Excellent |
| ID | Keywords Plus | 1 | 2.50 | Good |
| CR | Cited References | 2 | 5.00 | Good |
| DE | Keywords | 4 | 10.00 | Good |
| DI | DOI | 6 | 15.00 | Acceptable |

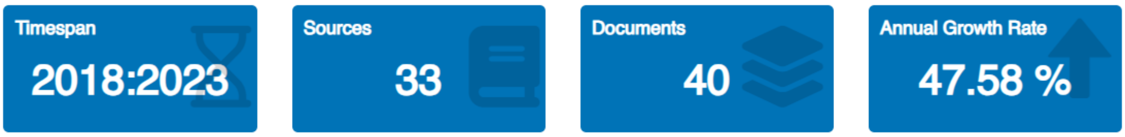


Figure 5. Main information of the dataset

The completeness of bibliographic metadata is crucial in any dataset, especially in academic research. Having complete and accurate metadata ensures the reliability and validity of the data for various analyses and investigations. Overall, this study indicates that the biographic metadata completeness of the dataset is of high quality, as the majority of categories have zero missing values and are labeled as "Excellent." However, some types, namely Keywords Plus, Cited References, Keywords, and DOI, exhibit missing counts ranging from 1 to 6, representing percentages from 2.50% to 15.00%. Despite these missing values, these categories are still considered "Good" or "Acceptable" in completeness. The dataset covers a timespan from 2018 to 2023, capturing research and information. It comprises data from 33 sources, including journals, books, and possibly other academic publications. In total, there are 40 documents available in the dataset. The data shows a notable annual growth rate of 47.58%, indicating a significant increase in the number of records added to the dataset over time. This growth rate suggests the dataset is continuously expanding, likely due to ongoing research and publication activities in the relevant fields.

### *Data screening*

In the data collection process, a selection was conducted based on the overall summaries of each article to determine their relevance to the research focus (Snyder, 2019). This initial screening facilitated the quick identification of studies potentially aligned with the research objectives. To maintain the integrity of the dataset, duplicated data were actively removed. This step was essential to avoid redundancy and ensure that each study contributed uniquely to the analysis (Linnenluecke et al., 2020). The primary focus was on XR technology specifically applied in educational contexts. Articles discussing XR technology in other fields were excluded, ensuring the review remained concentrated on educational applications. To minimize bias and enhance the validity and reliability of the review, a rigorous screening process was employed, involving the application of both inclusion and exclusion criteria. Table 2 details the inclusion criteria used in the screening process.

Table 2. Inclusion criteria and exclusion criteria

| Inclusion criteria | Exclusion criteria |
|---|---|
| ▪ Articles from reputable journal<br>▪ Available with full-text<br>▪ Educational research area<br>▪ Articles had to be written in English<br>▪ Timeframe: 2018 to 2023<br>▪ Specific Focus on XR in Education: "Extended Reality" or "XR" within the context of "Education." | ▪ Non-English articles<br>▪ Articles published before 2018<br>▪ Irrelevant Studies<br>▪ Duplicated or redundant articles. |

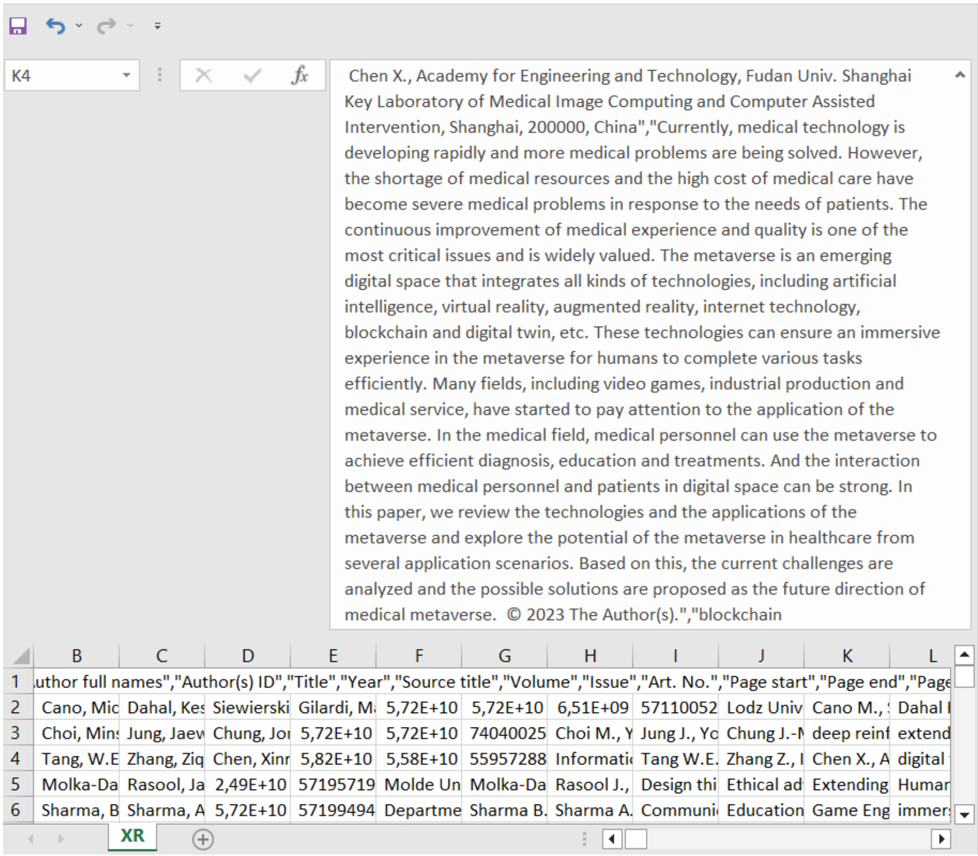


Figure 6. The screening process of summary

Figure 6 illustrates the screening process summary. This process was instrumental in ensuring the appropriateness and relevance of the selected studies for the review analysis. By adhering to these criteria, a comprehensive and accurate set of articles was obtained to effectively support the research objectives. No duplicate data were found, allowing for the evaluation of all 40 articles as a whole. Ensuring that the data used in the research did not contain duplicates was essential for providing more accurate and valid assessment results. With non-duplicate data, the article evaluation process could be carried out more effectively and efficiently, leading to more reliable conclusions for the overall research and analysis.

### *Eligibility and analysis*

After screening, a comprehensive content assessment of the articles was conducted to ensure the final data from the previously screened data collection. Each article was thoroughly read, evaluating the quality of their methodologies and the risk of bias in the studies. The final data were analyzed to address the research questions using R Studio, VOSviewer, Python, and MS Excel, as previously mentioned (Bukar et al., 2023). By following a systematic and transparent approach, the PRISMA review guidelines were adhered to, ensuring that the summary of the existing evidence was accurate, objective, and reliable (Aria & Cuccurullo, 2017).

During the content assessment phase, eight articles from the initial dataset of 40 were identified and excluded as they were deemed irrelevant to the research focus on the education sector. This exclusion was necessary to maintain the integrity and focus of the analysis. As a result, 32 final articles were further processed in the subsequent stages to address the research questions. The detailed results of the visual mapping, along with interpretations and conclusions, are presented in the results, discussion, and conclusion sections of our study. This comprehensive approach ensured that the findings were well-founded and that the conclusions were based on a thorough and critical examination of the existing literature on XR technology in education.

## 3. Results

### *Q1. Publication and citation trends of XR in education*

The dataset presents the annual count of published articles from 2018 to 2023. In 2018, authors published only one article; in 2019, there was an increase to three articles. A notable growth in publications occurred in 2020, with seven articles. This trend continued in subsequent years, where the number of articles rose to six in 2021 and significantly escalated to 16 in 2022. As of the current year, 2023, seven articles have been published thus far. The data showcases a prominent upward trajectory in academic publications over the years, indicative of a burgeoning interest and heightened research activity in the field of study, as shown in Figure 7.

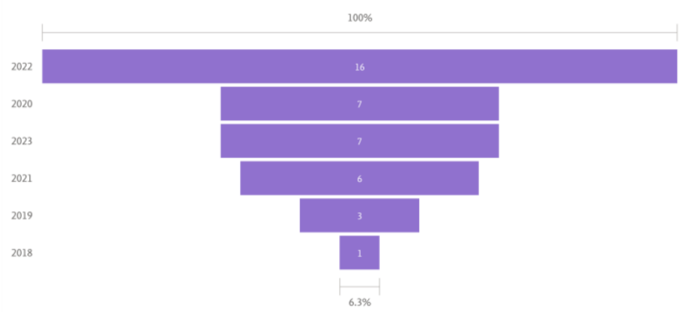


Figure 7. The sum of articles by year

Table 3. The top 5 most cited publications

| Paper | DOI | Total citations | TC per year | Normalized TC |
|---|---|---|---|---|
| (May, 2020) | 10.3991/ijoe.v16i03.12849 | 18 | 4,50 | 3,48 |
| (Matsika & Zhou, 2021) | 10.1016/j.techsoc.2021.101694 | 17 | 5,67 | 3,04 |
| (Wang et al., 2022) | 10.1109/TLT.2022.3210828 | 16 | 8,00 | 4,87 |
| (Low et al., 2022) | 10.1016/j.ece.2022.02.004 | 11 | 5,50 | 3,35 |
| (Rajaram & Nebeling, 2022) | 10.1145/3491102.3517486 | 8 | 4,00 | 2,43 |

*TC: Total citations*

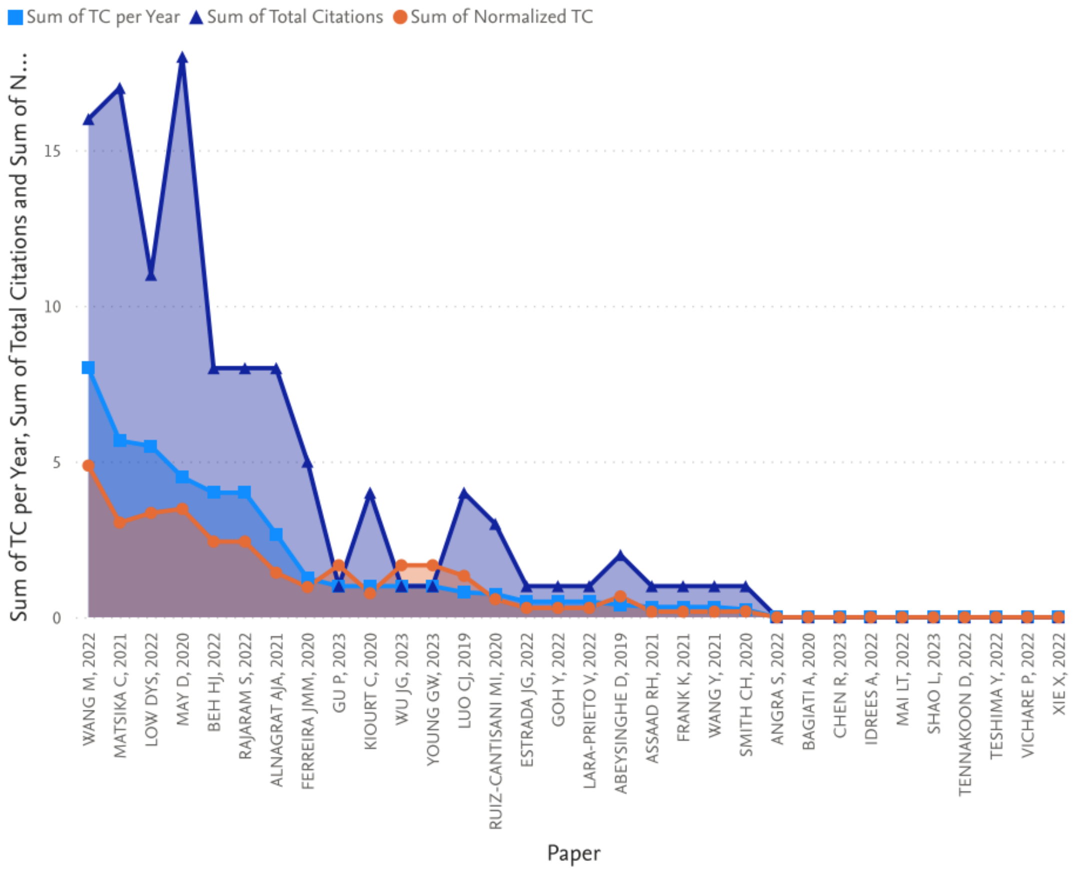


Figure 8. Total citations by year by authors

The dataset contains information on five research papers, encompassing the paper's title, total citations received, citations per year, and normalized total citation scores. Notably, the first paper, published in the International Journal of Online Biomedical Engineering in May 2020, has garnered 18 citations, demonstrating an average of 4.50 per year, with a normalized total citation score of 3.48. Similarly, the second paper, authored by Matsika and published in Technology in Society in 2021, has attained 17 citations, resulting in an average of 5.67 citations per year and a normalized total citation score of 3.04. The third paper, authored by Wang and published in IEEE Transactions on Learning Technologies in 2022, has received 16 citations, averaging 8.00 per year, with a normalized total citation score of 4.87. The fourth paper, authored by Low and published in Education in Chemical Engineering in 2022, has obtained 11 citations, reflecting an average of 5.50 citations per year and a normalized total citation score of 3.35. Lastly, the fifth paper, authored by Rajaram and presented at the Conference on Human Factors in Computing Systems in 2022, has garnered eight citations, with an average of 4.00 per year and a normalized total citation score of 2.43.

### *Q2. Countries with the most publications in XR research in education*

The study analyzes the frequency of scholarly papers on XR across multiple countries. The United States emerged as the foremost active contributor to XR research, having produced 19 articles, closely trailed by China with 17 publications and Canada with 11 publications. Following this, Greece was responsible for ten articles, and Malaysia and Mexico contributed nine and eight publications, respectively. The findings underscored the prominent positions the United States and China held in XR. Several factors could contribute to this dominance. First and foremost, both nations had sophisticated research and technology ecosystems that offered significant assistance and resources to researchers in the field of XR, enabling them to carry out their studies. Additionally, esteemed universities and research organizations specializing in technology and computer science served as a magnet for researchers from many backgrounds, resulting in a substantial impact on producing scholarly articles connected to XR (Figure 9).


Figure 9. Countries scientific production

Major technology corporations in the United States and China have fostered an environment conducive to advancing XR technologies. Supported by government initiatives and substantial corporate investments, both countries lead in the number of scholarly papers on XR. In the United States, companies like Facebook (now Meta) have allocated significant resources to develop XR-based metaverse platforms, reflecting strategic investments in XR research and development (Dwivedi et al., 2021; Kaddoura & Al Husseiny, 2023).

Meanwhile, China has prioritized XR as a key focus in their five-year plans, such as "Made in China 2025," aimed at enhancing the country's capabilities in high technology, including XR (Manfredi-Sánchez & Morales, 2024; Tse et al., 2024). This effort is bolstered by major technology giants like Tencent and Alibaba, which have made substantial investments in XR technology, underscoring their commitment to driving innovation and research in this field (Ma et al., 2024). Looking ahead, the continued dominance of the United States and China in XR development is poised to reshape the global technology landscape. With ongoing substantial investments and government support, both nations are poised to lead in delivering innovative XR-based solutions that not only transform how we interact with technology but also expand the boundaries of applications across various sectors, including education, healthcare, and industry (Ayoub et al., 2022).

### *Q3. Application of XR Technology in education*

XR technology enables a learning environment where experiences are at the core of knowledge formation processes. Through XR, students can interact and experience learning processes that closely resemble real-world conditions (Logeswaran et al., 2021). This technology stimulates the senses, fosters imagination, and engages students with high interest or admiration through audiovisual support of the subjects being studied (BL et al., 2024; Fitriyanti et al., 2023). This will increase attention and active engagement from students, enhancing their strong curiosity in learning something, thus making the learning process much more effective and meaningful (Fernández-Cerero et al., 2024; Sadanala et al., 2024).

Figure 10 illustrates the features of XR technology in education. XR expands the possibilities of learning across various dimensions, allowing students to experience sensations as if moving from one dimension to another (space, scale, and perspective). Furthermore, XR supports freedom in experimentation, meaning students can experiment without fear of risks and costs. For example, in assembling and manufacturing ship engines, students can safely engage in trial and error through 3D simulations (Barteit et al., 2021; Campos et al., 2022).

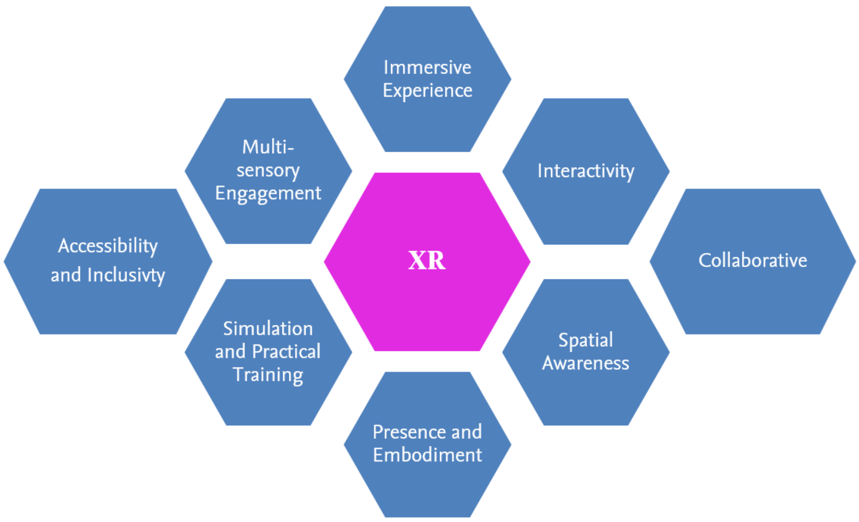


Figure 10. Features of XR technology in education

Additionally, XR technology in education offers a transformative range of features. It provides immersive experiences that transport learners into virtual worlds or historical simulations, enhancing engagement and making learning memorable (Dubovi, 2023; Heaysman & Kramarski, 2021). Learners can interact in real time with virtual objects, improving their understanding through spatial manipulation in three dimensions. XR also fosters presence and embodiment in virtual environments, facilitating deeper learning experiences (Maes et al., 2024; Southgate, 2020; Stanney et al., 2021). It enables practical training through realistic simulations, supports multi-sensory engagement for better concept retention, promotes collaborative learning environments, and enhances accessibility by accommodating diverse learning needs (Meccawy, 2023). These advantages collectively form a strong foundation for the application of XR technology in education, expanding the boundaries of traditional learning and delivering more profound, interactive, and comprehensive learning experiences for users.

XR has been implemented in various fields of knowledge to enhance user experiences, simulations, and understanding. In education, XR is utilized to create immersive and interactive learning environments (Estrada & Prasolova-førland, 2022), enabling students to experience more profound and engaging learning (Idrees & Morton, 2022), as exemplified by the integration of XR learning in electrical and energy engineering education (Takrouri et al., 2022). In the medical sector, XR is used for medical training (Logeswaran et al., 2021) and diagnostics (Shao et al., 2023), assisting doctors in better understanding patient conditions (Yue et al., 2021) and dealing with complex medical scenarios virtually (Abeysinghe et al., 2019). The fields of architecture and design also adopt XR for designing building and product simulations in 3D space (Mai & Werdin, 2022), enabling professionals to visualize their work outcomes before implementation. Additionally, XR has become an effective training tool for workers in industries and manufacturing (Assaad et al., 2022), enhancing efficiency and safety, such as in emergency training simulations (Ruiz-cantisani et al., 2020). Moreover, in arts and entertainment, XR is the foundation for creating films, games (Angra et al., 2022), and other entertainment content, providing unforgettable interactive experiences for the audience (Chen & Liao, 2023; Wu et al., 2024).

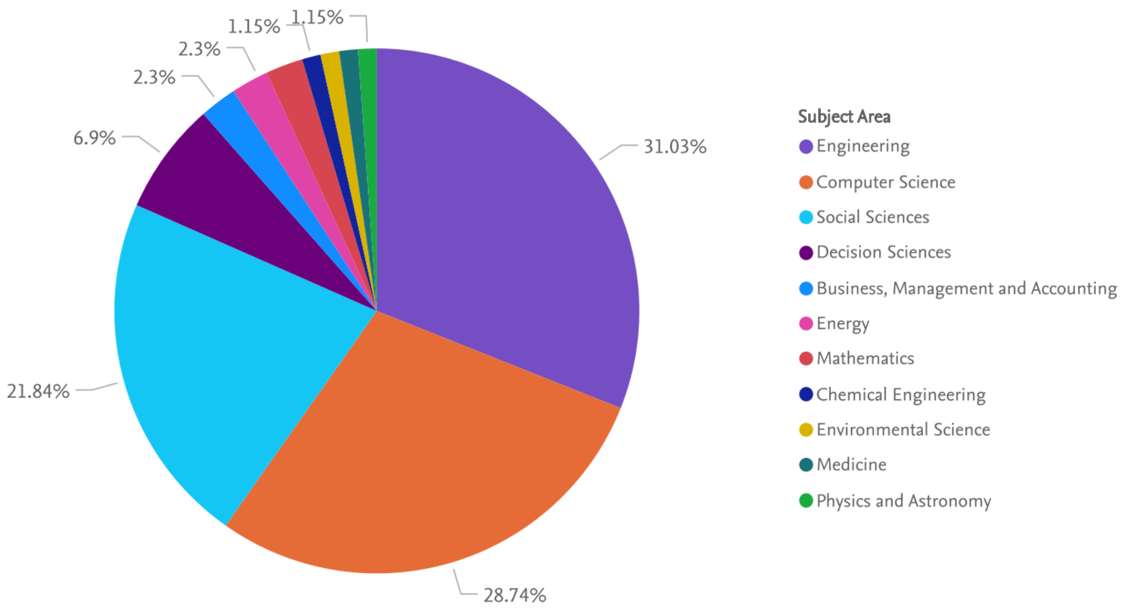


Figure 11. Distribution of the reviewed studies by subject area

Figure 11 shows that XR finds widespread application in education, particularly in engineering, computer science, and the social sciences. In engineering, researchers and educators utilize XR to create 3D simulations and visualizations (Lara-Prieto et al., 2022), which aid students in comprehending technical concepts better (Xie, 2022). For example, in mechanical engineering education, students can design and assemble virtual machines using XR, gaining practical experience in dealing with complex technical scenarios (Assaad et al., 2022). XR presents significant potential for interactive and immersive learning environments in computer science. Students can program, develop, and visualize solutions for complex software and systems, deepening their understanding of algorithms and cutting-edge technologies.

Additionally, in social sciences, XR is used to create immersive simulations of real-life situations, enabling students to better grasp various social and human behavior aspects. For instance, in psychology or sociology studies, XR can simulate social interactions and observe their impact on behavior and emotions. Overall, XR enriches the learning experience across these domains by providing hands-on, interactive, and authentic encounters, fostering a profound understanding of the subjects, and preparing students for real-world challenges (Wang et al., 2022).

By integrating XR into engineering, computer science, and the social sciences, educators significantly enhance students' learning experiences. Immersive technologies like AR, VR, MR, and XR are increasingly valued for their ability to facilitate more effective learning through visualization rather than purely theoretical approaches (Samala & Amanda, 2023). With XR, students can engage in more interactive, practical, and enjoyable learning experiences, fostering a deeper understanding of complex concepts. This indicates that using XR holds excellent potential for enriching teaching methods and improving students' learning outcomes across various disciplines.

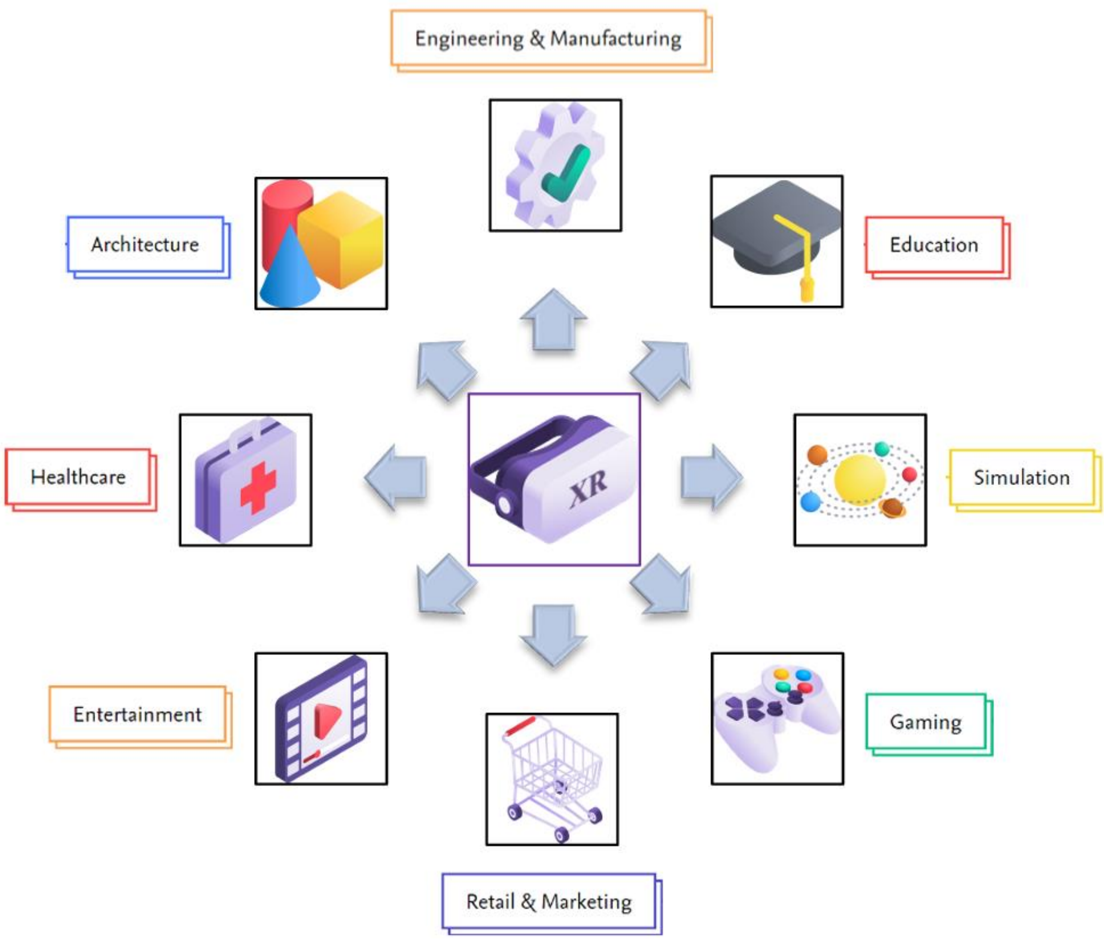


Figure 12. The application sectors of XR (Extended Reality)

In Figure 12, the sectors where XR technology finds application are classified based on data and analysis. Extended Reality (XR) spans various sectors, leveraging its capabilities to enhance experiences, efficiency, and innovation. The classification highlights the diverse and impactful applications of XR technology across different industries, showcasing its potential to drive significant advancements and improvements.

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To further understand the development and integration of XR technologies across varied sectors, it is essential to consider the meta layers framework. Meta layers serve as a comprehensive guide that ensures all aspects of immersive media technology development are addressed systematically. This framework organizes and categorizes various aspects or components within a system, offering a structured approach to understanding and managing the complexities involved. Here is a detailed explanation of each meta layer in the proposed framework as shown in Figure 13.

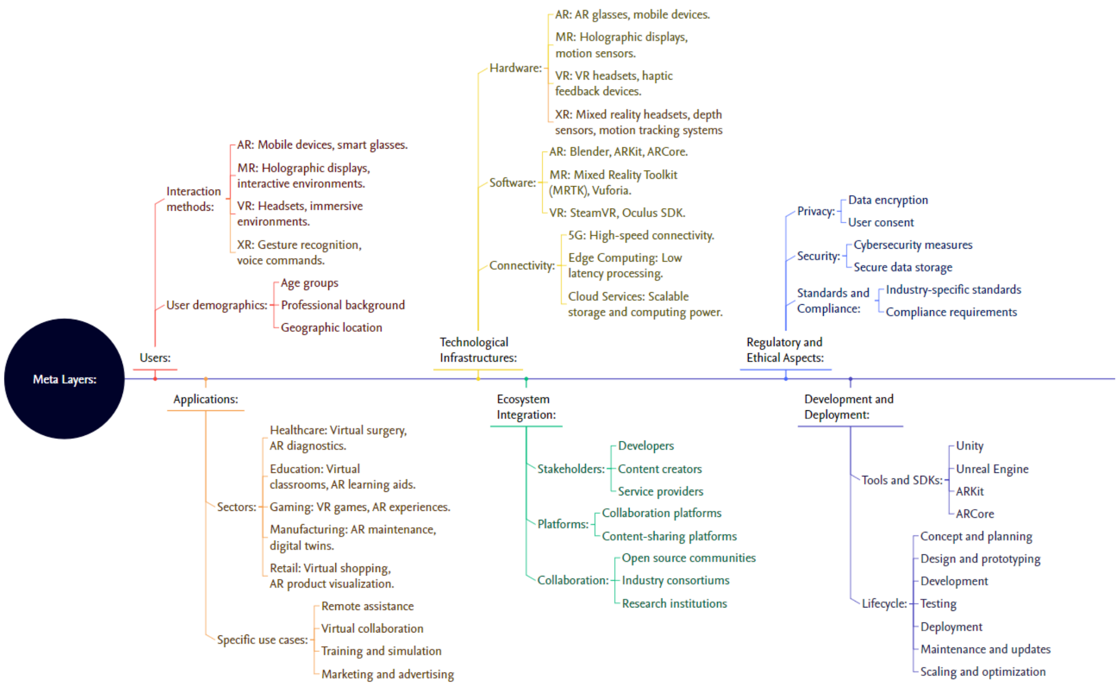


Figure 13. Meta layers framework

1) Users
   a. Interaction methods: The ways users interact with AR, MR, VR, and XR technology, including devices such as mobile devices, smart glasses, holographic displays, VR headsets, gesture recognition, and voice commands.
   b. User demographics: Information about the age groups, professional backgrounds, and geographic locations of users who use the technology.

2) Applications

   a. Sectors: The main sectors where immersive technology is used, such as healthcare, education, gaming, manufacturing, and retail.
   b. Specific use cases: Specific use cases within each sector, such as remote assistance, training and simulation, virtual collaboration, interactive learning, virtual classrooms, STEM education, immersive gameplay, virtual stores, marketing, and advertising.

3) Technologies infrastructure

   a. Hardware: The hardware used in immersive technology, such as AR glasses, mobile devices, holographic displays, motion sensors, VR headsets, and haptic feedback devices.
   b. Software: The software and SDKs used to develop immersive applications, such as

Blender, ARKit, ARCore, Mixed Reality Toolkit (MRTK), Vuforia, SteamVR, and Oculus SDK.

c. Connectivity: The connectivity technologies that support immersive applications, including 5G, edge computing, and cloud services.

4) Ecosystem integration

a. Participants: The participants in the immersive technology ecosystem, including developers, content creators, service providers, and end users.
b. Platforms: Collaboration and content-sharing platforms that support the development and distribution of immersive applications.
c. Collaboration: Forms of collaboration within the ecosystem, such as open-source communities, industry consortiums, and research institutions.

5) Regulatory and ethical aspects

a. Privacy: Privacy aspects that include data encryption and user consent to protect user data.
b. Security: Cybersecurity measures, access controls and secure data storage.
c. Standards: Industry standards and compliance requirements that must be followed in the development of immersive technology.

6) Development and deployment

a. Tools: Tools and SDKs used for developing immersive applications, such as Unity, Blender, Unreal Engine, ARKit, and ARCore.
b. Lifecycle: The lifecycle of application development, including concept and planning, design and prototyping, development, testing, deployment, maintenance, and updates, scaling and optimization.

Meta layers help organize and structure the various critical elements in technology development, making it easier to understand and apply in real-world projects. Finally, a well-defined development lifecycle, supported by the right tools and methodologies, ensures that projects are executed efficiently, from initial concept through to deployment and maintenance.

### *Q4. Current trending topics and challenges of XR in education*

The utilization of XR technology is still relatively limited in education, but its underlying technologies, such as VR and AR, have dominated and been widely used in educational contexts. Educators and researchers have extensively applied AR-based learning media across various academic levels, from elementary schools to universities. Further exploration of VR and AR applications in education demonstrates significant potential in enhancing students' learning experiences. With VR technology, students can "visit" distant and physically inaccessible places, such as historical sites, planets in outer space, or exotic natural environments as shown in Figure 14 and Figure 15.

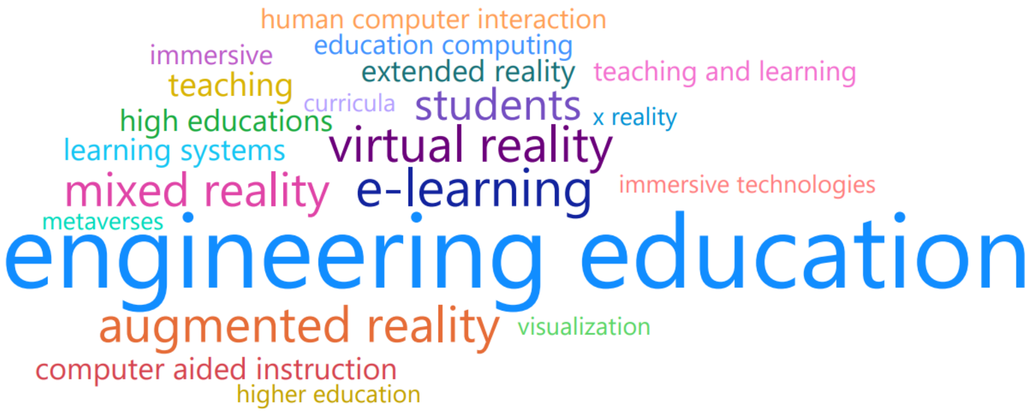


Figure 14. Current trending topics in XR in education

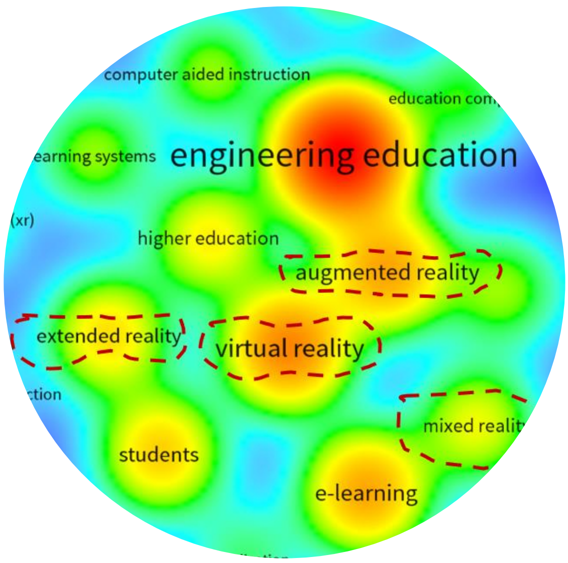


Figure 15. Density visualization: trends of XR in education

Consequently, VR technology enables students to engage in more profound learning experiences and connect knowledge with real-life encounters. Meanwhile, AR offers interactive and blended learning experiences with the real world. Students can access additional real-world content related to the subject matter using AR devices such as smartphones or tablets. For example, students can display 3D models of human organs on top of their science textbooks or showcase interactive examples of chemical reactions directly on the laboratory table. In the context of learning media development, AR presents a new and engaging way to give information and deliver course material visually and interactively. Integrating AR elements into textbooks or digital learning materials can enhance students' interest in learning and motivate them to participate in the learning process actively.

The challenges faced in using XR technology in education are diverse and complex (Beh et al., 2022). One of the main challenges is related to the significant cost involved. XR technology requires sophisticated hardware and software to create immersive experiences. The cost of acquiring these devices can be a barrier for many educational institutions with budget limitations. Technical challenges also need to be addressed. Utilizing XR technology necessitates a strong and stable infrastructure and network to support smooth experiences. Regulation is also a crucial factor in implementing XR technology in education.

The use of XR technology in educational settings must consider existing privacy policies and regulations to protect the personal data of students and other users. Limitations in resources and infrastructure are also challenges to using XR technology. Not all educational institutions have adequate access to the necessary hardware and software to implement XR in their teaching practices.

Additionally, prolonged use of headsets can lead to discomfort, nausea, or even physical injury. Users may also experience confusion and inadvertently collide with real-world objects, posing additional physical risks. In this context, attention to user health and safety is crucial in implementing XR technology in educational settings. Moreover, literacy and digital skills pose significant challenges. Using XR technology requires specialized understanding and skills in operating and utilizing the devices effectively for learning. Educators and students need to be trained to optimize the use of this technology properly. Addressing these challenges ensures that XR enhances educational experiences while mitigating potential risks and maximizing its benefits in learning environments.

## 4. Discussion

The discussions and conclusions of this study revolve around the application and challenges of XR technology in education. Throughout the analysis, it became evident that while the use of XR in education is still relatively minimal, its underlying technologies, such as VR and AR, have gained significant traction and widespread adoption in various educational settings. The development of AR-based learning media has been extensively implemented in elementary, secondary, and tertiary education, showcasing the potential for immersive and interactive learning experiences. The findings from the bibliometric analysis indicate that the dominant disciplines where XR has been applied in education are engineering, computer science, and the social sciences. These disciplines have capitalized on XR to create realistic simulations, enhance visualization, and promote hands-on experiences, thus deepening learners' understanding of complex concepts (Marougkas et al., 2023).

However, several challenges must be addressed despite the promising prospects of XR in education. The primary hurdles include substantial costs associated with acquiring XR hardware and software, technical complexities in infrastructure and network support, regulatory compliance concerning data privacy, limited access to XR resources in certain educational institutions, and the need for improved digital literacy and digital skills among educators and students (Hamilton et al., 2021; Prabhakaran et al., 2022).

In an in-depth discussion, the transformative potential of XR technology in education cannot be overstated. One of the most compelling aspects of XR is its ability to create highly immersive learning environments that closely mimic real-world scenarios. This feature is particularly beneficial in fields such as medical training, where students can practice surgical procedures in a risk-free virtual environment, or in engineering, where complex machinery can be assembled and disassembled without the physical limitations and costs associated with actual equipment.

Moreover, XR's capability to visualize abstract concepts in 3D can significantly enhance comprehension and retention. For instance, in STEM education, students can interact with molecular structures, witness astronomical phenomena, or explore anatomical systems in ways that traditional 2D representations cannot match. This hands-on approach facilitates active learning and encourages students to engage more deeply with the subject matter.

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Additionally, XR fosters collaboration and social learning by enabling students to interact in virtual spaces. This is particularly advantageous in a globalized education landscape, where students from different geographical locations can collaborate on projects, participate in virtual field trips, or attend lectures from world-renowned experts without leaving their homes. The social aspect of learning is further enhanced by the sense of presence and embodiment that XR provides, making virtual interactions feel more personal and engaging.

Regardless these advantages, the path to integrating XR into mainstream education is fraught with challenges. The high cost of XR hardware and software remains a significant barrier, particularly for underfunded educational institutions. Furthermore, the infrastructure required to support XR technologies, including high-speed internet and robust network systems, is not universally available, creating a digital divide that could exacerbate existing educational inequalities (Lampropoulos & Kinshuk, 2024).

Regulatory and ethical considerations also pose challenges. Ensuring data privacy and security in XR environments is paramount, especially when dealing with minors (Zallio & Clarkson, 2022). Additionally, developing guidelines and standards for XR content to ensure it is pedagogically sound and accessible to all learners, including those with disabilities, is crucial. Finally, the success of XR in education hinges on the digital literacy of both educators and students. Professional development programs are essential to equip teachers with the skills and confidence needed to integrate XR into their teaching practices effectively. Likewise, students must be trained to navigate and utilize XR tools responsibly and effectively.

## 5. Conclusion

In conclusion, while XR technology remains nascent in education, the increasing adoption of VR and AR indicates a growing interest in and acceptance of immersive learning experiences. The potential of XR in enhancing the quality of education is substantial, but addressing the challenges mentioned above is crucial for its widespread integration. Collaborative efforts among governments, educational institutions, technology industry stakeholders, and the public are imperative to overcome these challenges and unlock the full potential of XR technology in transforming education and creating more engaging and effective learning environments. By embracing the opportunities and addressing the barriers, educators can revolutionize how knowledge is imparted and received, paving the way for a more immersive, inclusive, and impactful educational landscape in the digital era.

### *Limitations and future works*

This review study acknowledges several limitations that could impact the comprehensiveness of its findings, primarily due to the exclusive reliance on the Scopus database for data acquisition. While Scopus is widely recognized as a reliable and extensively used database, it may not encompass all relevant papers on XR in education. Many alternative databases and platforms contain significant research and ideas within this field, potentially overlooked by confining searches to Scopus, resulting in compromising the study's scope and comprehensiveness.

To address these constraints and enhance the robustness of future research, it is recommended to conduct more comprehensive inquiries across a broader array of databases and sources. Integrating multiple databases such as Web of Science, Google Scholar, and specialized repositories can provide a more holistic understanding of the current status of XR in education. Additionally, exploring non-English language papers is crucial as they may offer unique perspectives and insights on XR deployment in educational settings, thereby mitigating potential biases inherent in relying solely on English-language publications.

To advance future research, an iterative approach is proposed to regularly review accumulated research evidence and facilitate cross-sectoral knowledge sharing to identify best practices and pathways for widespread XR implementation. Moreover, employing a blend of qualitative and quantitative research methods—including case studies, interviews, focus groups, and bibliometric analysis—can enrich scholarly rigor and offer deeper insights into XR's educational potentials and challenges. Furthermore, for the responsible integration of new technological features like AI, transparency, sustainability, and ethical considerations are essential.

This review provides crucial insights into the current state of XR in education but acknowledges limitations, particularly in data sources and potential language bias. To enhance future research reliability, a more comprehensive methodology is proposed, including a broader range of databases, languages, and research methodologies. These techniques will allow for a more effective investigation of XR's transformative potential in education, significantly contributing to the adoption of educational technology based on empirical data.

## Author contribution

Agariadne Dwinggo Samala: Conceptualization, methodology, formal analysis, software, resources, investigation, visualization, supervision, writing—original draft, and writing—review and editing. Ljubisa Bojic: Conceptualization, formal analysis, investigation, validation, and writing—review and editing. Soha Rawas: Formal analysis, investigation, validation, and writing—review and editing. Natalie-Jane Howard: Methodology, formal analysis, validation, and writing—review and editing. Yunifa Miftachul Arif: Formal analysis, resources, and writing—review and editing. Dana Tsoy: Conceptualization, validation, and writing—review and editing. Diogo Pereira Coelho: writing—review and editing. All authors have approved the final manuscript.

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## Conflict of interest

The authors declare no conflict of interest.

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