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XR and Workers' safety in High-Risk Industries: A comprehensive review

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ABSTRACT

The wider application of extended reality (XR) in various industrial settings has created numerous opportunities for enhancing worker safety. Several XR solutions have been applied to address specific safety challenges faced by workers. This study reviewed the current literature (2017–2024) on how XR technologies can potentially enhance worker safety. The PRISMA protocol was used to highlight how XR technologies are utilized in safety training for high-risk industries, their limitations, and recommendations for future improvements. Findings from a review of 41 studies indicate diverse opportunities (e.g., improved knowledge and productivity, delivery of interactive and sequential instructions) for virtual reality (VR), augmented reality (AR), and mixed reality (MR) in industries such as mining, construction, manufacturing, healthcare, power distribution/thermal plants, aviation, and firefighting. Several challenges (e.g., limited viewing fields, motion sickness, and control issues) were identified in the use of VR, AR, and MR, stemming from both human and socio-technical factors. The overall sentiment towards the use of XR in safety training was predominantly positive (550 instances), reflecting confidence in these technologies to enhance safety training outcomes. Findings from this study offer new insights into the capabilities of XR technologies in improving worker safety in high-risk industries and outline key considerations for policymakers and technology providers when integrating XR technologies to promote worker safety.

1. Introduction

Safety training is a key component of workplace safety management systems, particularly in high-risk occupations. It includes learning interventions that equip new and existing employees with the knowledge, skills, and competencies required to perform assigned tasks safely and effectively (Dodoo et al., 2023). Research has shown that safety training improves safety behaviours, enhances job-related attitudes, and enables workers to perform their jobs safely (Dodoo & Al-Samarraie, 2019). The effectiveness of safety training is significantly influenced by the methodology used. Traditional training methods, however, have notable limitations, including lower learner engagement, poor retention, high costs, and lack of motivation due to their passive learning approach (Kierzkowski et al., 2024). They are also ineffective in accurately presenting hazards in a realistic manner (Gualtieri, Revolti & Dallasega, 2023).

Given the above, advancements in 3D digital twins—a virtual representation of a physical object, system, or process based on real-time data used to mirror the behaviour and characteristics of its physical counterpart—have proven useful for safety training. It is noteworthy that research has used the terms "3D digital twins" and "virtual prototypes" interchangeably to describe a 3D virtual reality (VR)-based model that mimics real-world objects, systems, or environments (Cecil & Kanchanapiboon, 2007). The characteristics of virtual prototypes, such as appearance, simulation, representation, and interface criteria, have contributed to safety training in various ways. Digital twins offer opportunities to improve the safety and efficacy of risk management in the workplace (Gualtieri, et al., 2023). Extended reality (XR) includes VR (a three-dimensional environment experienced through a head-mounted display), AR (which overlays virtual objects onto the real-world environment in real-time, viewable via a smartphone, tablet, or AR headset), and MR (which integrates digital content with the real-world environment in real-time, viewable through an MR headset). These technologies offer interactive and immersive experiences that can significantly enhance learner engagement and retention, reduce costs, and motivate learners through active participation. As a result, digital innovative technologies are increasingly adopted to revolutionise safety training, industrial work processes, and the management of occupational safety

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and health in high-risk industries (Dodoo et al., 2024; Gualtieri, et al., 2023; Shah & Mishra, 2024).

Current literature suggests that XR technologies have the potential to enhance the effectiveness of safety training compared to traditional methods (Arif et al., 2024; Kierzkowski et al., 2024). For example, Osti et al. (2021) explored the potential of using a simulated VR learning environment to train novice workers in wooden wall construction, resulting in better performance and engagement among workers compared to traditional training methods. Eiris et al. (2018) developed an AR tool to support construction workers in learning hazard identification on work sites. The authors argued that using AR in safety training can help create engaging platforms to improve workers' hazard-identification skills. Elrifaee (2023) stated that AR and VR can significantly enhance bridge construction site safety training by using a pre-training model and allowing trainees to choose their preferred movement approach, which can further improve the training's effectiveness. Other studies have examined XR's role in improving physician comfort, technical skills, and spatial awareness of procedures (Gagandeep et al. (2021) and its cost-effectiveness in equipping workers with skills and knowledge for handling disaster and emergency response situations (Berthiaume et al., 2024). Based on these practices, it can be concluded that different forms of XR have been widely used to promote workplace safety in high-risk industries.

Previous reviews (e.g., Doolani et al., 2020; Lee & Wong, 2019; Muñoz-La Rivera et al., 2024; Ross & Gilbey, 2023; Zoleykani et al., 2024) have emphasised that advances in visual and haptic display technologies have led to improved work performance, safer worker behaviour, and a reduction in accidents and fatalities. For example, several notable review studies on XR have limited their focus to understanding recent trends in VR and MR applications in construction safety (Moore & Gheisari, 2019), ophthalomology education (Ong, Tan, Lam, & Koh, 2021), emergency management in built environment (Zhu & Li, 2021), and in sports (Noury, Polman, Maloney & Gorman, 2022). Arif et al. (2024) focused their review on how serious games support medical education, while Shah and Mishra (2024) examined the role of artificial intelligence in managing occupational safety and health. In their review, Strzałkowski et al. (2024) and Sudiarno et al. (2024) highlighted the relevance of VR-based training for promoting safety, efficiency, and profitability in high-risk workplaces.

Although these reviews have investigated the use of XR in safety management, few have provided a thorough focus on XR application in safety training for high-risk industries (see Table 1). For instance, the majority of review studies primarily focused on understanding the extent of XR application in specific industries. Meanwhile, less attention was given to understanding the challenges associated with the use of XR systems, particularly their impact on safety training in high-risk industries. Meanwhile, it is clear that safety training is a critical driver for promoting workplace safety. These observations indicate a gap in understanding how XR (e.g., VR, AR, and MR) might contribute to worker safety within high-risk industries through safety training. To address this gap, this paper aims to: (a) explore the application of XR technologies in safety training for high-risk industries, (b) identify challenges impacting the effectiveness of XR-based safety training, and (c) provide future research directions on the implementation of XR technologies in safety training.

This review is significant for comparing current trends in the deployment of XR for workplace safety training, highlighting critical challenges, and offering recommendations to system designers and users for decision-making. It expands the conversation on XR (AR, VR, and MR) for safety training, provides information on challenges affecting the utilisation of the various types of XR, and proposes a way forward. The findings highlight specific industry needs and requirements for increasing the effectiveness of XR-enabled safety training. This will be particularly useful to system designers and practitioners in building and designing human-centred systems, as well as in increasing usage and effectiveness. The remainder of the paper is organised as follows: Section Two describes the methods used in retrieving, processing, and analysing previous studies; Section Three presents and visualises the results of this study regarding the potential of VR, AR, and MR in enhancing workers' safety in high-risk industries; Section Four addresses the main challenges of using XR in safety training; Section Five discusses the practical implications and limitations of this work; and Section Six concludes the study.

Table 1
Summary of previous review literature on XR and safety.

Purpose	XR Type	Reference
Focused on the safety-related application of VR-MR techniques.	VR & MR	Moore & Gheisari, 2019
Reviewed the current status, challenges and future development of XR in the management of intracranial tumors.	VR & AR	Lee & Wong, 2019
Identified the usefulness of XR in ophthalmology education.	VR	Ong, et al., 2021
Examined the application, benefits and inefficiencies of XR in emergency management in the build environment.	VR & MR	Zhu & Li, 2021
Utilisation of XR technology in Sports.	VR, AR, & MR	Noury, et al., 2022
Explored state of knowledge on use of XR technology for flight training	XR	Ross & Gilbey, 2023
Examined the use of serious games in medical education	VR, AR & MR	Arif, et al., 2024
Examined XR usage and identified factors affecting contruction safety and its integration into building information modelling.	VR, AR, & XR	Muñoz-La Rivera et al., 2024
Examined the application of XR technologies in construction safety from the perspective of project lifecycle.	XR	Zoleykani et al., 2024

2. Methods

This study followed the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) guidelines by Page et al. (2021) to systematically screen and review previous studies. For this study, XR in safety is defined as the use of various immersive technologies, primarily VR, AR, and MR, to enhance worker safety in high-risk industrial settings. Examples of such settings include mining, agriculture, construction, forestry, and other industries with similar characteristics (Dodoo et al., 2024). A bibliometric analysis was then conducted on the extracted data to explore trends and the distribution of publications on XR in safety over time.

2.1. Identification of the literature

A literature search was conducted to identify relevant studies from the following databases: Scopus, Web of Science, and ProQuest. These databases were chosen due to their academic credibility and extensive coverage. A set of keywords was carefully selected to systematically retrieve English-language studies focused on the application of XR in workplace safety, published between January 2017 and January 2024. This time frame was chosen due to the significant acceleration in the adoption and integration of XR technologies—encompassing VR, AR, and MR—since 2017. Our review of experimental studies on XR applications across industries in 2017 revealed a shift from experimental and pilot projects to more widespread implementation across diverse workplace contexts, including high-risk sectors such as construction, oil and gas, and manufacturing. The search keywords included: ("immersive technology*" OR "immersive space*" OR "immersive environment*" OR "immersive experience*" OR "extended reality" OR "XR" OR "augmented reality" OR "AR" OR "virtual reality" OR "VR" OR "mixed reality" OR "MR") AND ("safety" OR "risk" OR "hazard*" OR "health management" OR "care" OR "protection" OR "aid") AND ("workers" OR "employees" OR "labourers") AND ("safety" OR "care" OR "protection" OR "aid"). We included peer-reviewed journal articles, conference papers, and systematic reviews to ensure a comprehensive overview of the current state of research. The review did not impose methodological delimiters (e.g., only outcome evaluations). Unpublished reports (e.g., theses and dissertations, policy/practitioner reports, and conference communications) were also considered throughout the search period.

2.2. Eligibility/Inclusion criteria

To ensure a relevant selection of previous studies, we used the following predefined inclusion criteria:

1. Application of XR: Studies must have examined the application of XR technologies, including VR, AR, and MR, in various contexts.
2. Focus on Workers' Safety: Previous studies should specifically address issues related to workers' safety within a workplace environment.
3. Specific Workplace Settings: The studies need to detail the use of XR within specific workplace settings to help understand how specific XR technologies are integrated and utilised in those environments.
4. Empirical Evidence: Studies must provide empirical evidence supporting their findings. This includes data obtained through descriptions, correlations, regressions, and other methods of evaluation and usability studies.

Studies that focused exclusively on theoretical discussions or opinion pieces were excluded from the review. Fig. 1 illustrates the screening process employed to select the relevant studies based on these criteria.

2.3. Data extraction

The initial literature search led to the inclusion of 936 studies from selected databases (707 from Scopus, 225 from Web of Science, and 4 from ProQuest). Another 21 studies were identified through reference searches and the first 10 pages of Google Scholar, resulting in a total of 957 articles. All the retrieved studies underwent a two-stage screening process: 1) screening of titles and abstracts, and 2) full-text screening based on predefined inclusion criteria. In the first stage, a total of 242 duplicate studies were excluded, resulting in 615 unique articles. After reviewing titles and abstracts, 463 studies were excluded, mainly due to

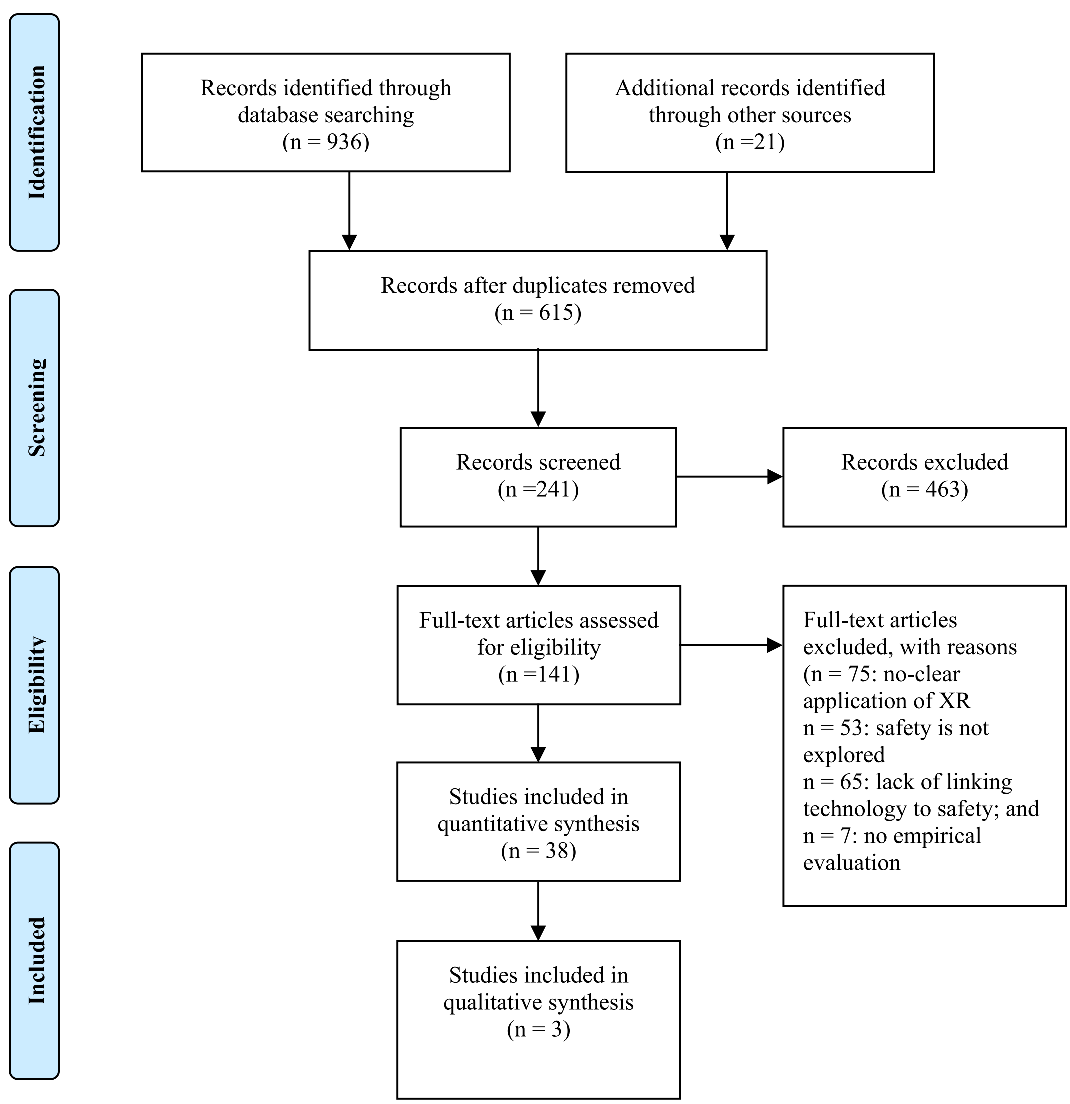

Fig. 1. The PRISMA flowchat.

irrelevance to workplace safety or being opinion-based rather than empirical research. This led to the inclusion of 252 articles. Of these, 11 were not accessible, resulting in 241 articles. Further screening using the developed eligibility criteria led to the exclusion of studies due to unclear application of XR (n = 75), lack of exploration of workers' safety (n = 53), lack of connection between XR and safety (n = 65), and no empirical evaluation (n = 7). Through this process, 41 articles were confirmed for inclusion in this review, as shown in Fig. 1.

2.4. Grouping the studies and quality check

To synthesise the findings on the use of XR in workplace safety, the identified studies were organised into a table with multiple columns (study features) and rows (studies). The 41 studies were grouped by the first and second authors based on the following criteria: 1) study purpose, 2) XR characteristics used by workers, 3) industrial context where safety was evaluated, 4) findings from the XR interventions, 5) challenges, and 6) implications for the examined context. The first two features were deemed important for reviewing the relevance of the selected studies in relation to the type of XR in safety contexts, fulfilling the first and second selection criteria. The third feature ensured that each article was situated within specific high-risk settings. The fourth feature recorded how specific XR technologies contributed to safety training, helping to answer the first research question. The fifth feature captured the main limitations and challenges, aiding in answering the second research question. The sixth feature supported the identification of future recommendations and answering the third research question.

Given the expertise and background of the first and second authors, they independently evaluated the selected papers for quality control. We developed four criteria (scored 1–4) to evaluate the quality of the papers: 1) Appropriateness of XR technology in safety; 2) Relevance of the industrial context (high-risk); 3) Appropriateness of study objectives in answering the research questions; and 4) Appropriateness of the study type (empirical). We used the literature matrix to review the final list of studies based on the above criteria. We then used a spreadsheet to gather the scores for each study for further analysis. Interrater reliability was assessed to evaluate the quality of the articles using Krippendorff's alpha. The alpha value of agreement among the experts was 94 %, which is above the 80 % criterion (strong agreement).

Colour-coding (e.g., distinct colours to represent different types of XR technology—AR, VR, and MR) was used to identify patterns, compare topics, and highlight differences in usage within the developed literature matrix. This was done alongside an iterative discussion process, which helped us reach a consensus on the naming and content of the codes (sub-factors). Through this coding process, four specific dimensions (themes) were identified: wearable-based systems, augmented/virtual-based systems, artificial intelligence-based systems, and navigational-based systems. The identification of these dimensions was based on the types of technologies found in the collected articles and their application to specific industrial contexts.

2.5. Bibliometric analysis

In order to gain initial insights from the 41 collected studies, we applied bibliometric analysis to explore the profile, trends, and sentiments related to the use of XR in safety training. First, we created a.bib file of the 41 studies, including authors, titles, keywords, abstracts, year of publication, and type of XR technology. We then imported the.bib file into the R environment to automate and facilitate the analysis. Topic modelling (see Jelodar et al., 2019) was employed to identify the top terms in the literature. A number of preprocessing steps in R were carried out to clean and normalise the textual data. These included: 1) transforming all text in the corpus to lowercase for consistency and to avoid treating the same words differently; 2) removing punctuation marks from the text to prevent possible misinterpretation caused by punctuation being part of a word; 3) eliminating all numeric characters from the text to focus the analysis on the actual content, excluding numbers that might not contribute meaningfully to the topic modelling process; 4) removing commonly used words (stopwords) that do not carry significant meaning (e.g., "the," "and," "in"); and 5) removing extra whitespace from the text to ensure the data was clean and ready for subsequent analysis. After this, we extracted the document-topic matrix from the Latent Dirichlet Allocation model to understand the distribution of topics across the documents, followed by checking the document-topic matrix to show how topics were distributed within the documents. We then plotted the top terms for each topic.

Moreover, the sentiments expressed in the abstracts of the collected studies were extracted and visualised using the Syuzhet library in R. This process involved analysing the abstracts to identify the emotional tones conveyed in the text. We then summarised the sentiment scores by aggregating them across all documents, providing an overall view of the various sentiments (e.g., joy, trust, fear, anger) found in the abstracts. Finally, we created a bar plot to visualise the distribution of sentiment scores across the different sentiment categories.

3. Results

3.1. Bibliometric results

The empirical studies reviewed demonstrate the application of XR across various industries, including construction, mining, manufacturing, healthcare, power distribution/thermal plants, aviation, and firefighting (see Supplementary for the list of studies). Fig. 2 illustrates the diverse utilisation of XR in these sectors from 2017 to 2024. Table 2 provides a detailed breakdown of the types of XR technologies used in these industries. Notably, the construction, healthcare, and firefighting sectors exhibit the most diverse utilisation of XR installations for safety-related purposes.

The results of the topic modelling for AR, VR, and MR in safety training show distinct focuses for each technology (see Fig. 3). AR was mostly linked to "interaction," "education," and "healthcare," which reflect its role in engaging users and enhancing accessibility. VR was mainly linked to "simulation," "construction," and "usefulness," making it ideal for realistic, practical experiences in high-risk industries. MR was focused on "effectiveness," "training," and "control," indicating its strength in structured training environments. Each technology was found to offer different opportunities in safety training, with AR being more interaction- and education-focused, VR excelling in simulation and practical applications, and MR being prominent in effective training and control scenarios.

The sentiment analysis results (see Fig. 4) of the literature on the application of XR in safety training were predominantly positive, with 550 instances of positivity significantly outweighing negative sentiments (49 occurrences). Specifically, trust was the most frequently expressed sentiment (299 occurrences), which might imply that researchers have confidence in the effectiveness and potential of XR technologies for enhancing safety training. In addition, anticipation was the second most common sentiment (161 occurrences). Furthermore, fear emerged as a significant sentiment (105 instances), reflecting concerns related to the adoption of XR technologies in safety contexts. Sadness and anger were less prevalent but still present, with 84 and 49 occurrences, respectively. These emotions may be linked to the challenges or limitations of integrating XR into safety training. Joy was reported 86 times, which might reflect positive emotions linked to the successful implementation and outcomes of XR in safety training. Surprise and disgust were also notable, with 56 and 37 instances, respectively.

3.2. Virtual reality (VR)

The findings from the review showed that the use of VR technology in safety training can be categorised into three levels: non-immersive,

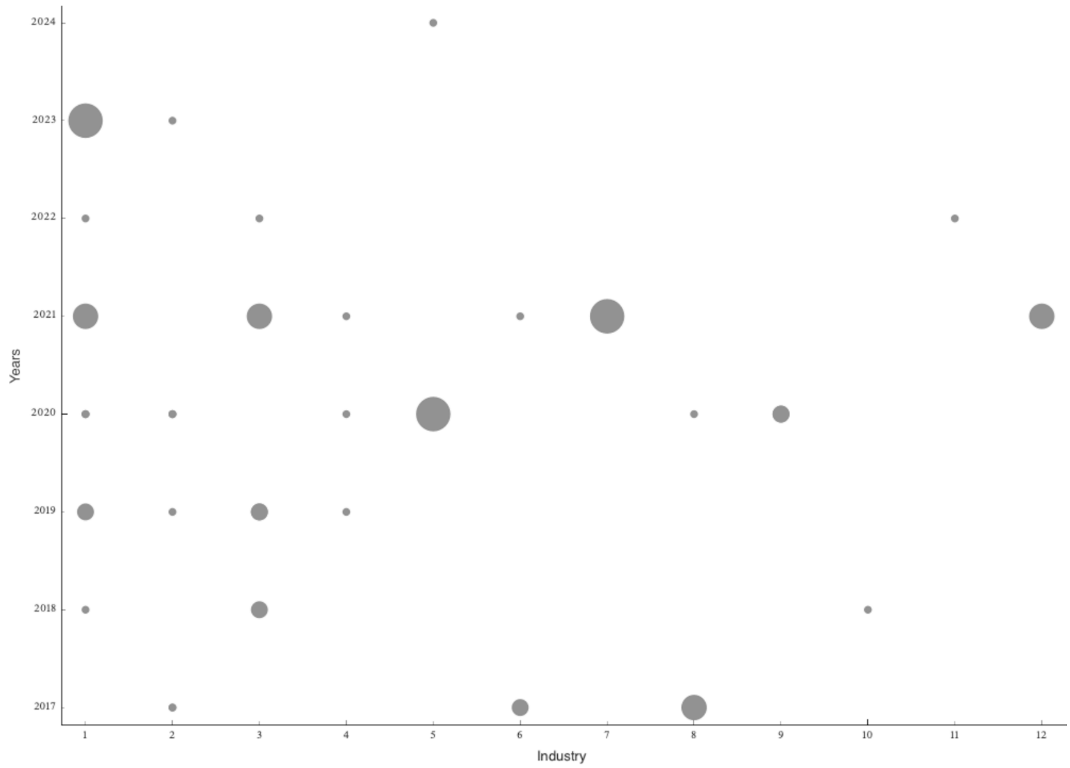

Fig. 2. XR use in industries from 2017 to 2024 [1 > Construction; 2 > Mining; 3 > Healthcare; 4 > Manufacturing; 5 > Firefighting; 6 > Power Plant; 7 > Multi-industrial set-up; 8 > Aviation; 9 > Aerospace; 10 > Railway; 11 > Steel Plant; 12 > OSH Plant].

Table 2
Use of XR technologies in industries for safety training.

	VR	AR	MR	XR
Construction	x		x	x
Mining	x			
Healthcare		x	x	
Manufacturing	x			
Firefighting	x			x
Power Plant		x		
Multi-Industrial set-up	x			x
Aviation			x	
Aerospace		x		
Railway	x			
Steel Plant	x			
OSH Plant			x	

semi-immersive, and fully immersive.

Non-immersive VR: This involves using standard monitors and interaction devices like keyboards or a mouse, or an enhanced 3D interaction device to facilitate workers' interaction with training materials via a window on a standard monitor (Cecil, Albuhamood & Ramanathan, 2017; Elrifaee, 2023).

Semi-immersive VR: This level combines high-performance graphics with large screen projectors or multiple display projections, widening the field of view and enhancing the immersive experience. Special input devices, such as handheld controllers or data gloves, provide an intuitive way for workers to interact with virtual training spaces while maintaining awareness of their physical surroundings, without feeling fully transported into the virtual world (Cecil, et al., 2017; Macias-Velasquez et al., 2024).

Fully immersive VR: This provides the most direct and complete interactive safety experience using a head-mounted display device. Multi-sensory setups, such as motion trackers and haptic feedback devices, provide users with a more realistic sense of presence, improving workers' interaction and learning of safety processes (Cecil, et al., 2017; Elrifaee, 2023).

Our review identified that fully immersive VR (Zhang, 2017), semi-immersive VR (Liang et al., 2019; Pedram et al., 2017; Stiles et al., 2018) and non-immersive VR (Kim et al., 2021; Perez-Ramirez et al., 2021; Stiles et al., 2018) systems have supported safety training in high-risk industries in different ways. Specifically, the integration of VR technology in safety training for high-risk industries has led to improved safety knowledge, increased awareness of hazard identification, and generated a number of intrinsic benefits.

Studies in the mining industry found that VR-enabled safety training increased safety knowledge and productivity among mine workers (Zhang, 2017). In addition, it was largely perceived as an efficient method for providing emergency training, allowing trainees to visualise and learn their tasks quickly, while serving as a stress-free and safe training method (Kaarlela et al., 2020). VR simulations provided an intuitive understanding of disasters by simulating complex underground mining environments (Li et al., 2020) and offered a better user experience in terms of immersion, interaction, and ease of use (Zhang, 2017).

Furthermore, the findings showed that VR-based safety training led to increased safety awareness and risk aversion in an efficient manner, which improved workers' hazard identification (Liang et al., 2019). The immersive VR gaming experience provided a sense of enjoyment and presence in safety training (Pedram et al., 2017). Additional factors contributing to the success of VR-based safety training include high levels of engagement, the perceived fidelity of scenarios, a sense of co-presence with other trainees, perceived usability, and a positive attitude towards technology (Pedram et al., 2020). These findings indicate that VR-based training is an effective methodology for occupational safety and health training in the mining industry (Gürer et al., 2023).

In the construction sector, VR-based safety training fostered collaboration among workers and served as a reliable feedback tool for safety management (Kazar & Çomu, 2022). The study by Jeelani et al. (2020)

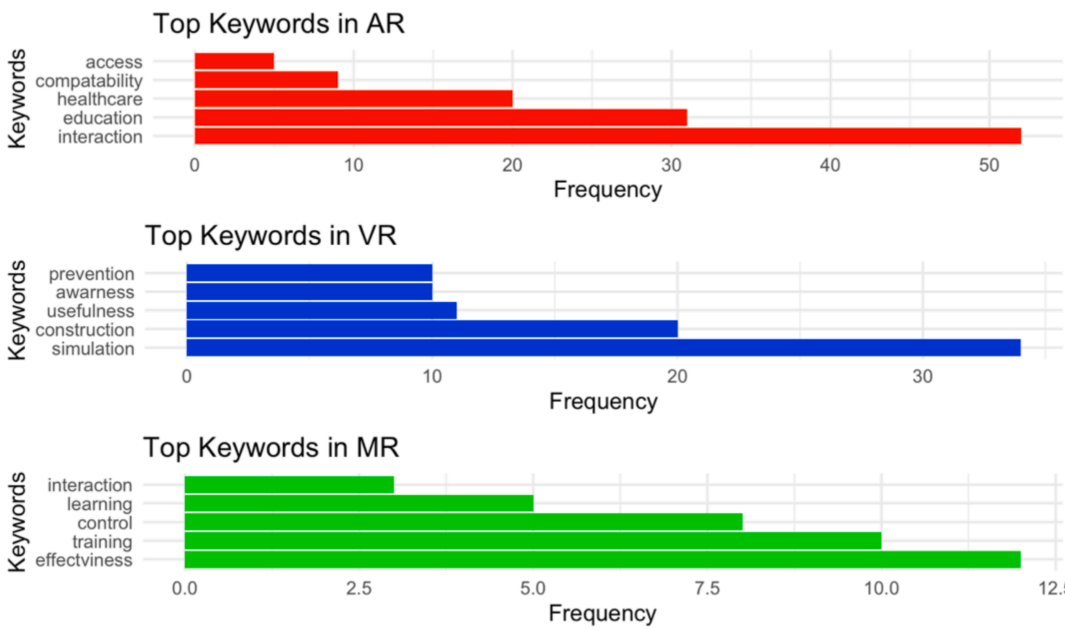

Fig. 3. Top terms (n:5) for each technology.

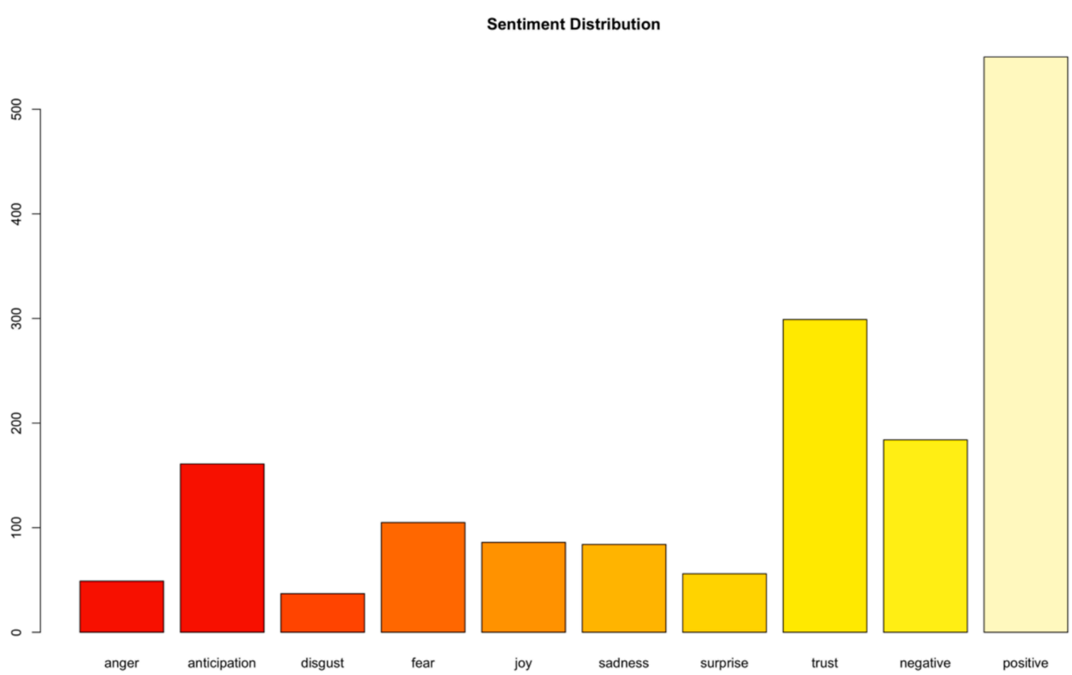

Fig. 4. XR sentiments in safety.

showed that VR-based safety training improved hazard identification and management performance, and increased training efficiency through an enhanced understanding of safety and health concepts. Eiris et al. (2020) found that VR's immersive and highly present experience reduced time wasted during hazard identification. The perceived interactive learning environment provided by this technology is critical for the success of safety training in high-risk industries. According to Jacobsen et al. (2021), the VR-based safety training method served as an active learning environment that supported the analysis and evaluation of users' basic safety and productivity performance. In addition, the use of run-time data collection and automatic analysis allows for personalised feedback during safety training.

In the manufacturing context, we found that the simulation environment provided by VR-based safety training increased safety risk consciousness, induced positive emotions, and enhanced retention of safety knowledge (Lacko, 2020). For example, Pratticò and Lamberti (2021) compared the use of immersive VR training with traditional in-class and hands-on training methods, revealing that immersive VR safety training supported task completion more effectively. Similarly, Dhalmahapatra et al. (2022) found that the VR training method helped trainees identify potential causes of accidents and assisted them in understanding how such hazards could be mitigated in the plant.

The review findings further showed that the VR-based safety training method has been widely applied across various sectors such as healthcare, railway operations, power distribution/thermal plants, aviation, and firefighting. For example, in the field of healthcare, the VR-based safety training method supported the safe design and use of laser radiation (Owczarek et al., 2021). found that both immersive and non-immersive VR outperformed traditional training methods in aviation procedural training, enhancing safety knowledge retention and confidence. In power distribution/thermal plants, Perez-Ramirez et al. (2021) observed that the use of VR-based safety training decreased accident rates during live-line maintenance and guided workers safely through routine activities. In the railway context, Stiles et al. (2018) reported that the use of 360-film VR technology raised safety awareness, introduced engagement, and reduced distractions. Furthermore, Heirman et al. (2020) developed VR simulators using the HTC VIVE Pro kit and ZED Mini stereo camera technology for safe firefighting training at a Navy school. It was found that the system supported the efficient training of firefighters in challenging situations safely. Meanwhile, VR training tools were used to teach firefighters how to approach dangerous scenarios safely. The findings from simulation training showed high usability, acceptance, and satisfaction with the VR training tools (Berthiaume et al., 2024).

The findings from the review showed that VR-based safety training could potentially support safety performance by increasing safety knowledge, hazard identification, awareness, and improving hazard management. It provided a simulated environment that enhanced workers' understanding of environmental risk hazards and mitigating measures. The findings also revealed that VR-based safety training introduced efficiency in transferring safety knowledge, potentially enhancing the productivity and safety performance of high-risk industries. Furthermore, the immersive experience of VR training was perceived as fun and provided a sense of enjoyment and co-presence, which potentially enhanced safety training performance. The simulated environment could increase engagement and collaboration among workers and offered a stress-free training method compared to the traditional paper-based form of providing safety training.

3.3. Augmented reality (AR)

Our review revealed that high-risk industries have adopted AR-enhanced digital visualisations to support employee safety training. This approach has been applied in industries such as healthcare, construction, power thermal plants, and aerospace/aviation. AR has been useful in promoting discovery-based learning through enhanced visualisation and interaction with both virtual and real-world environments (Lin & Yu, 2023).

Tatić and Tešić (2017) argued that inadequate training and a lack of work experience were the primary causes of injuries in the power-thermal industry. To mitigate these issues, they proposed the use of mobile devices with AR technology to provide step-by-step instructions to workers. This approach aimed to fill the training gap by offering interactive and sequential instructions, which decreased error rates and workplace injuries. Moreover, it was observed that AR served as an interactive on-the-job training method, providing workers with practical safety knowledge to work safely. Although the AR app provided a just-in-time source of safety training and modified safety behaviour, understanding how the system supports safety knowledge retention and long-term safety behaviour was lacking. Therefore, gaining this understanding would be of immense benefit to scholars and practitioners.

In the construction industry, we found two studies that applied AR for safety training purposes. Eiris et al. (2018) addressed gaps in traditional safety training methods (such as passive lectures, videos, and demonstrations) by using 360-degree panoramic AR technology as an alternative. The cost-effective technology allows trainees to visualise real job sites and supports safety training. The 360-degree panoramic images were augmented with safety data to engage trainees actively in exploring, visualising, and practising hazard identification. The technology enhanced workers' hazard recognition skills and supported them in evaluating the likelihood of injuries before starting an activity. In a related study, Kim et al. (2019) developed and implemented a new AR-based assessment tool using Microsoft HoloLens to evaluate the hazard recognition skills of construction major students in a construction safety course. The immersive AR-based environment provided a realistic visual context for real-world safety hazard identification. Participants found it enjoyable and effective for identifying real-world hazards. Future research should explore the efficacy of safety knowledge acquired via AR technology in real-world environments, which will be of tremendous value to both practitioners and researchers.

Further, our review identified studies that have applied AR for safety training purposes in the healthcare sector. For example, Balian et al. (2019) tested a novel AR CPR training system that used computer-generated imagery to create interactive training scenarios. A CPR training manikin was integrated with an AR device (Microsoft HoloLens) to provide users with real-time audio-visual feedback through a holographic overlay showing blood flow to vital organs. Results indicated that participants were satisfied with the system, with 82 % perceiving the experience as realistic, 98 % finding the visualisations helpful for training, and many expressing willingness to use the system in the future. The current study proposes expanding access to safety training by applying the AR-based CPR training method to non-healthcare professionals. This simulated training experience is particularly important for non-practitioners to acquire basic life support knowledge. Further supporting the argument for AR-based safety training, Escalada-Hernández et al. (2019) designed and evaluated a prototype app for mobile devices using AR technology. This aimed at addressing the lack of sufficient instructional information on the use of medical devices, which potentially increased errors. The Android-based AR system was described as highly intuitive, providing users with detailed instructional information about different medical devices. It also assists users, especially less experienced professionals, in easily handling new or complex medical devices. The AR technology supported clinical practice by providing handy instructions for using or operating medical devices. Moreover, Tang et al. (2018) implemented AR technology for mammographic training. The AR-based approach was able to digitally record and distinguish every single operation, allowing for individual and automatic analysis of each breast cancer feature. This method was considered an easier way of handling and interpreting health results (Lacey et al., 2022).

In the aerospace/aviation industry, AR technology has been widely applied for safety training. For example, Nezhad et al. (2020) developed an AR system integrated into aircraft composite bonded assembly and repair to guide technicians through repair operations to eliminate human error tendencies and reduce assembly and repair duration. The AR application blended digital mockups with physical panels and patches using pre-set image target recognition. AR was also found to serve as a digital and automatic way to instruct the composite bonded assembly and repair process. The toolkit reduced processing time, fortified process reproducibility, promoted product quality, and enhanced operators' skill levels. Further, Alarcon et al. (2020) assessed the maturity of AR technology for transferring safety knowledge, enhancing workplace performance, and ensuring safety in space activities.

Although AR holds long-term potential, many enabling components were not fully mature to meet the space industry's requirements. This study views AR-based safety training as promising for reducing workplace errors and enhancing the quality of work life for workers and clients. However, how the system can seamlessly translate into real-life work experience remains unclear, presenting a gap worthy of further research. Our view is that the use of AR technology in safety training promotes interactive and engaging sessions, providing an immersive experience that helps learners better understand safety instructions. AR-based safety training offers simulated environments that enhance learners' ability to handle workplace risks and hazards efficiently. Lastly, it provides a fun experience for workers, potentially reducing anxiety and stress associated with encountering dangers in high-risk industries, thereby improving hazard identification and overall safety performance among workers. Further research is needed to explore the long-term impacts of AR-based safety training on knowledge retention and real-world application.

3.4. Mixed reality (MR)

MR represents the merging of real-world and virtual-world elements, creating a composite environment where these objects interact (Moore & Gheisari, 2019). Its application in safety training provides increased immersion through features such as head tracking, hand tracking, eye tracking, haptics, and 360-degree imagery (Volkow & Howland, 2018). Our review revealed that MR has proven particularly beneficial in construction and firefighting safety training. For instance, Dai et al. (2021) argued that traditional forms of hazard communication in construction, such as phone calls or video conferencing, are inadequate for hazard identification on construction sites. They explored MR as an alternative, using a prototype holographic application that allowed the manipulation of the field of view on MR head-mounted displays to create a collaborative real-time environment. The findings demonstrated that MR enhanced visualizations of risks and hazards in the work environment, contributing significantly to the accuracy and effectiveness of risk communication. Moreover, MR supported remote collaboration on safety-related issues more effectively than traditional methods.

Heirman et al. (2020) developed MR simulators using the HTC VIVE Pro kit and ZED mini stereo camera technology for firefighter training at a Navy school. Their findings indicated that MR-supported safety training provided efficient and safe firefighter training. Similarly, Gonzalez-Franco et al. (2017) compared MR technology with traditional safety training methods to evaluate collaborative learning effectiveness. They used a mixed reality setup comprising a modified Oculus Rift DKI HMD with a 1,280 x 800 resolution (640 x 800 per eye) and a 110-degree diagonal field of view. A pair of cameras mounted on the HMD formed a see-through MR setup, enabling real-time collaborative interactions and simulated conventional training methods. The findings showed no significant difference in knowledge retention between MR-based and traditional training methods. However, MR-based training facilitated earlier task completion compared to traditional methods, underscoring its ability to enhance engagement in learning. Rauh et al. (2021) sought to understand perceived attitudes towards MR training usage and feedback. Their study used the Microsoft HoloLens 1, equipped with a set of different environment-sensing cameras developed in Unity3D to create a multiplatform game engine and development environment. Their findings revealed that MR could extend theoretical occupational safety and health teaching methods. This finding highlights the need for a smooth integration of both traditional face-to-face and MR-based training methods in delivering safety training. The study further revealed that the MR experience motivated employees to actively engage in training sessions.

Based on the above, it can be said that MR enhances hazard identification, risk communication, and remote collaboration in industries like construction and firefighting. This is primarily due to its interactive nature, which improves engagement and motivation among trainees, fostering effective learning outcomes. Thus, integrating MR with traditional methods offers a comprehensive approach to safety training, promising significant advancements in workplace safety practices and culture.

4. Associated challenges of using XR in safety training

Our review identified several challenges associated with the use of XR systems in high-risk industries, stemming from both human and socio-technical factors (see Table 2). For instance, users noted that the VR system architecture restricted their movements, thereby reducing immersion (Zhang, 2017). In addition, slower response times due to cloud rendering hardware (Kaarlela et al., 2020) were identified as another limitation hindering workers' adoption of VR technology. Users criticised the visual design of V-SAFE.v2 for its unrealistic depiction and failure to capture all aspects of the work environment (Kazar & Çomu, 2022). Other limitations identified with VR technology included issues with image quality (Eiris et al., 2020), which could potentially produce erroneous data collection due to the parameters used for detecting hazards (Jacobsen et al., 2021), and challenges with immersion and quality of interface (Joshi et al., 2021).

Further challenges include limited viewing fields, poor signal, and loud noise, which affect users' VR experience, making it difficult to hear, wear, and walk while using it (Zhang et al., 2022). Kim et al. (2021) identified challenges such as fogged lenses due to masks, system heaviness, heat, and small screen size. Onososen et al. (2023) reported that real-life construction conditions posed difficulties for VR systems in accurately simulating these environments, potentially affecting their effectiveness in safety training. In the study by Dias Barkokebas and Li (2023), aspects of the VR system, such as the virtual lifting of heavy materials in the real environment, were found to be difficult to capture.

In addition, it was observed that motion sickness was a major challenge in relation to the use of VR for safety training (Berthiaume et al., 2024; Lacko, 2020; Liang et al., 2019; Zhang, 2017). Jeelani et al. (2020) noted the difficulty in assessing the long-term impact of VR training on workers' ability to recognise hazards. Our findings also highlight limitations such as small sample sizes and the preliminary nature of some studies, which restrict generalisation to real-life settings. The literature also points to challenges like the lack of pre-training on technology use (Elrifaee, 2023). Furthermore, VR use was perceived to increase workload due to high mental, physical, and temporal demands, and users reported frustration with its use (Berthiaume et al., 2024).

From an AR perspective, users are likely to encounter problems with the interface and control methods, which can limit user experience and engagement (Kim et al., 2019). Moreover, challenges related to image quality, static vantage points, and parallax stitching were found to restrict the effectiveness of AR systems in providing safety training (Eiris et al., 2018). These issues encompass image recognition, positional accuracy, system synchronisation, and compatibility with various scenarios (Nezhad et al., 2020).

The main challenges identified with MR systems in safety training range from inefficiencies in system design to human factors. For instance, insufficient brightness in the HoloLens prevented users from fully experiencing the virtual world, causing eye strain and potentially impacting hazard recognition and training effectiveness (Rauh et al., 2021). The element of authenticity in MR simulations for firefighting was found lacking, with participants noting that MR simulation training was incomparable to real hot fire training (Heirman et al., 2020). Human factors included feelings of anxiety among first-time users of MR systems (Gonzalez-Franco et al., 2017) and a lack of acceptance of MR as an effective system for delivering safety training (Dai et al., 2021).

5. Recommendations

Safety training is crucial for enhancing workplace safety and the well-being of workers. The application of various technologies has proven effective in high-risk industries in improving workers' understanding of training instructions and increasing engagement. Our review indicates that while these systems facilitate faster transfer of safety knowledge, enhance learner engagement, and promote safety awareness and behaviour, they face challenges that impede system efficiency. To sustain the effectiveness of VR, AR, and MR in enhancing safety knowledge and workplace safety, we have identified recommendations (see Table 3) for practitioners, system designers, and researchers to consider. These recommendations are categorised as follows:

1. VR: The study recommends upgrading both the hardware capacity and software design of VR systems. It is suggested that advanced VR headsets with head straps and haptic controllers be integrated into the system architecture. This would enhance hazard recognition during safety training. It is also worth mentioining that improving

Table 3
A summary of XR challenges and recommendations in high-risk industries.

Industry / Technology	VR	AR	MR	XR	Challenges	Recommendation	References
Mining	x				Limited movements; motion-sickness/ dizziness; limited sample; cloud rendering; system test	Upgrade of hardware and software to comply with the latest standards mandated for VR interaction; Larger sample for testing; control training time	Zhang (2017); Pedram et al. (2017); Kaarlela et al. (2020); Li et al. (2020); Liang et al. (2019);
Construction	x	x			Limited user interface and control methods; lack of pre-training models; dizziness; difficulty in mimicking real-life conditions; mixed effects of display types.	Adapt user-centered design approach; provide pretraining models; improve VR functionality	Eiris et al. (2018); Kim et al. (2019); Elrifaee (2023); Onososen et al. (2023); Liu et al. (2023); Dias Barkokebas and Li (2023)
	x				Unrealistic visual components; long-term impact; image quality; erroneous data collection; limited number of users using the system; immersion and quality of the interface; limited viewing fields; difficulty wearing and walking with the system	Capture real site conditions; use advanced VR headset with head-straps and haptic controllers; improve immersion and quality interface	Kazar and Çomu (2022); Jeelani et al. (2020); Eiris et al. (2020); Jacobsen et al. (2021); Joshi et al. (2021); Zhang et al. (2022)
			x		Lack of usability and acceptance	Certain features in MR require adequate training to enhance acceptance	Dai et al. (2021)
Power thermal plant		x			n/a	n/a	Tatić and Tešić (2017)
	x				n/a	Integrate other technologies to improve immersion	Perez-Ramirez et al. (2021)
Railway	x				n/a	n/a	Stiles et al. (2018)
Healthcare	x			x	Small screen size; touch sensors; fogged lenses with masks; heaviness; heat after a period of time.	Invest in lightweight VR headsets with high computing and resolution power	Kim et al. (2021)
		x			Reduced training duration; uncertainty; vibration; inability to view information.	Provide a cyclic dataflow; enhance usability and user satisfaction; improve hand hygiene quality and reduce face-to-face instruction	Balian et al. (2019); Escalada-Hernández et al. (2019); Tang et al. (2018); Lacey et al. (2022)
Aerospace/ aviation		x			Image recognition; positional accuracy; system synchronisation; high customisation costs; lack of standard, off-the-shelf solutions; and incompatible devices.	Use of hands-free displays (such as projectors and Smart glasses)	Nezhad et al. (2020); Alarcon et al. (2020)
	x				n/a	n/a	Buttussi and Chittaro (2020)
			x		MR set-up	Training	Gonzalez-Franco et al. (2017)
Firefighting	x		x		Incomparability with the task; motion sickness; oculomotor symptoms; and disorientation.	Introductory training	Heirman et al. (2020); (Berthiaume et al., 2024)
Manufacturing/ Steel plant	x				Object identification; motion sickness	Implement multi-user scenarios	Owczarek et al. (2021); Pratticò and Lamberti (2021); Dhalmahapatra et al. (2022); Lacko (2020)
			x		Insufficient brightness	MR training	Rauh et al. (2021)

the immersive experience and quality of the interface is necessary to minimise challenges related to motion sickness that users experience with VR technology. This improvement would also contribute to user satisfaction, promote safety learning behaviours, and provide better feedback. Furthermore, providing pre-training to trainees would alleviate their apprehension during their initial encounter and boost their confidence in using the VR system. The review also suggests integrating VR technology with other emerging analytics-based safety management systems to enhance the system's capabilities and suitability for safety training in high-risk industries. It is also recommended to conduct further research using a broader population to better understand various factors influencing safety training, such as the level of immersion, optimal content, frequency, and training delivery methods.

2. AR: The review found that improving the user interface has a significant direct influence on user experience. It is recommended that system designers consider enhancing usability and features that increase user satisfaction to improve user acceptance and system usage. To address challenges related to high customisation costs, it is recommended that hands-free displays, such as projectors and smart glasses, be considered, as they may be more effective. Moreover, to address challenges regarding the system's capabilities, further comparison of the results of AR-based training with traditional training methods will help validate the system's effectiveness in providing real-time safety training in the workplace.
3. MR: The study recommends upgrading the features of MR systems and providing adequate training to enhance user experience and acceptance. Another key recommendation is to address insufficient brightness by enhancing the MR learning application, which should include tailored training to help minimise the stress associated with first-time use of MR-based training systems.

6. Practical implications

The findings reported in this study offer several practical implications for the industry, system designers, and researchers. Based on these findings, it is suggested that high-risk industries balance technological advancements with human-centred considerations in order to maximise the effectiveness of XR technologies in the safety training of their workers. We call on industry players to focus more on human–computer interaction in the design and implementation of XR technologies. This approach will have two implications. First, it will lead to an upgrade of both hardware and software components of XR systems to address technical limitations such as image quality, system heaviness, and motion sickness. Second, it will ensure that human factors (cognitive, physical, and emotional) are fully integrated into the system to enhance user experience and system effectiveness.

Further, we propose that future research focus on the integration of XR and artificial intelligence (AI) to promote workplace safety. It is envisaged that this integration could potentially improve the intelligence of the system, which would have implications for the efficiency and effectiveness of safety training. It could also enhance usability and trust in the use of innovative technologies to prevent accidents, injuries, and fatalities in high-risk industries. To enhance XR's effectiveness in promoting workplace safety, it is also crucial to consider the integration of advanced features, such as haptic controllers, and to improve system immersion in order to enhance user experience and satisfaction. Doing so could potentially contribute to the acceptance and usability of XR technologies among workers.

Moreover, providing adequate pre-training to users can reduce initial apprehension and boost confidence in using these technologies, especially for those with limited technological experience. We consider this step to be particularly important for first-time users who may experience anxiety or discomfort during their initial exposure to XR systems. We believe that integrating XR with other emerging safety management systems could further enhance its capabilities by making it more robust and better suited to meet the diverse safety needs of workers. From a broader perspective, it is also recommended that industries consider the cost-effectiveness and scalability of XR technologies. Hands-free displays, such as projectors and smart glasses, may offer a more practical solution for widespread adoption, especially in environments where traditional training methods are still predominant. Furthermore, promoting ongoing research and development is necessary to continuously improve XR systems and ensure they remain effective in providing real-time, relevant safety training.

7. Limitations and future research

There are a number of limitations that should be considered in future research. For example, our search of previous studies was restricted to those published between 2017 and 2024, and the selection of studies focused specifically on research directly examining the use of XR in safety training in high-risk industries. This narrow scope may have excluded other relevant studies that could provide additional context or insights. As such, we suggest that future research consider broadening the scope and extending the search period to capture a more comprehensive range of studies. Doing so could expand the understanding of the evolving role of XR in safety training, potentially identifying new trends, challenges, and opportunities. Meanwhile, further studies could investigate the long-term impact of XR-based safety training on workers' hazard recognition abilities and overall workplace safety, as well as explore the potential of integrating XR with other emerging technologies in safety management.

8. Conclusion

This study investigated the application of XR technologies in the safety training of workers within high-risk industries. The study identified and discussed the emerging opportunities that XR technologies bring to safety training across sectors such as mining, construction, power-thermal, railway, healthcare, aerospace, aviation, firefighting, and manufacturing. The results reported the effectiveness of XR-based interventions for safety training in several key areas: creating an immersive and simulated learning environment that facilitates the efficient transfer of safety knowledge; enhancing trainee engagement, collaboration, and confidence; reducing anxiety; and providing a stress-free learning experience. Trainees' reactions to XR-based learning often include a high degree of immersion and co-presence, which are perceived as enjoyable and motivating, thereby enhancing the overall learning experience. The impact of XR-based safety training was also evident in improving hazard identification and awareness, better management of workplace risks, and increased productivity and safety performance. Despite these significant benefits, the study also identified several challenges, particularly those related to human factors and the socio-technical aspects of XR systems. These challenges, which range from technical limitations such as system heaviness, motion sickness, and visual design flaws, to human factors such as anxiety and lack of acceptance, are likely to hinder the widespread adoption and effectiveness of XR technologies in safety training.

CRediT authorship contribution statement

Joana Eva Dodoo: Writing – review & editing, Writing – original draft, Resources, Conceptualization. **Hosam Al-Samarraie:** Writing – original draft, Supervision, Methodology, Conceptualization. **Ahmed Ibrahim Alzahrani:** Writing – review & editing, Writing – original draft, Supervision, Software, Resources. **Tang Tang:** Writing – review & editing, Visualization, Validation.

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Declaration of competing interest

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Data availability

No data was used for the research described in the article.

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