

Recent advances in virtual reality applications for construction safety management

Kun WANG^a, Maxwell Fordjour ANTWI-AFARI^{b*}, Beatrice Mensimah OSSEI-GUDOM^c,
Wen YI^d, Jue LI^e, Saeed BANIHASHEMI^f,

^aDepartment of Civil Engineering and Management, School of Engineering, The University of Manchester, Manchester, M13 9PL, United Kingdom. Email: kun.wang-7@postgrad.manchester.ac.uk

^bDepartment of Civil Engineering, College of Engineering and Physical Sciences, Aston University, Birmingham, B4 7ET, United Kingdom. Email: m.antwifari@aston.ac.uk

^cBartlett School of Sustainable Construction, University College London, London, WC1E 6BT, United Kingdom. Email: beatrice.ossei-gudom.21@ucl.ac.uk

^dDepartment of Building and Real Estate, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong SAR. Email: wen.yi@polyu.edu.hk

^eSchool of Economics and Management, China University of Geosciences, Wuhan, Hubei, China. Email: lijue16@cug.edu.cn

^fSchool of Built Environment, Faculty of Design, Architecture & Building, University of Technology Sydney, 15 Broadway, Ultimo, NSW 2007, Australia. Email: saeed.banihashemi@uts.edu.au

***Corresponding author:**

Department of Civil Engineering, College of Engineering and Physical Sciences, Aston University, Birmingham, B4 7ET, United Kingdom. Email: m.antwifari@aston.ac.uk.

Recent advances in virtual reality applications for construction safety management

Abstract

Purpose – To improve construction safety management, the application of virtual reality (VR) has been demonstrated for workers' safety training and hazard recognition. Although previous review studies have been conducted on VR applications in construction safety management, the recent advances in current uses, challenges, and future research directions are still unexplored. Moreover, no framework has been developed to explore VR-based safety directions within the construction industry. Therefore, this paper conducts a systematic literature review and develops a conceptual framework of the current uses, challenges, and future research directions of VR applications for construction safety management.

Design/methodology/approach – The research methods adopted a systematic literature review (i.e., PRISMA guidelines). In total, 58 included articles were retrieved from the Scopus database.

Findings – It was found that the current uses of VR applications include (1) safety training and education (55%), (2) safety risk management (19%), (3) hazard identification (14%), and (4) prevention through design. (12%) In addition, the challenges facing the adoption of VR applications include (1) technology (software and hardware), (2) social acceptance, (3) culture influence, (4) risk compensation, and (5) cost-effectiveness. Based on the identified challenges, future research directions were proposed.

Originality – This review study proposed a framework highlighting future research directions that could help other researchers and practitioners mitigate these challenges and improve construction safety management. Ultimately, it contributes to advancing the theoretical and practical applications of VR technology in construction.

Keywords: Construction industry; Safety management; Systematic literature review; Virtual reality

Paper type: Literature review

1. Introduction

The construction industry is a complex and dynamic sector that offers employment opportunities for numerous individuals and contributes to national development (Zhou *et al.*, 2015; Adami *et al.*, 2021). The global workforce employed in the construction industry constitutes about 7% of the total workforce, generating about 6% of the global gross domestic product (GDP) (Adami *et al.*, 2021). Nevertheless, occupational injuries and fatal accidents within the construction industry tend to exceed those in other industries (Zhou *et al.*, 2015). According to the U.S. Bureau of Labor Statistics (2022), it was reported that construction and extraction occupations ranked second in terms of occupational fatalities in 2021, with a total of 951 deaths. Despite the efforts to improve occupational health, wellbeing, and safety among construction workers, the construction industry still faces significant risks, fatalities, and challenges. As such, numerous health and safety concerns in the construction industry need critical attention, measures, and precautions.

Safety management is a commonly utilized approach to regulate construction activities and mitigate risks associated with a construction project, which involves the manipulation of on-site safety policies and procedures (Zhou *et al.*, 2013). The practices of safety management could be defined as implementing effective safety management strategies, and stakeholders aiming to maintain control over potential hazards and ensure a safe working environment (Li *et al.*, 2021; Zhou *et al.*, 2013). The long-standing perception that safety is closely linked to management has led many construction practitioners and researchers to prioritize cultural intervention, the adoption of safety behaviors, organizational ideologies, etc. (Mullan *et al.*, 2015). According to Reason (1998), safety culture plays a pivotal role in workplace incidents. Design and construction risks are more likely to occur, and infractions are frequently overlooked in a setting where there is a poor safety culture at work (Reason, 1998). Zohar (1980) discovered that there is a relationship between safety climate and safety audit scores. In the construction industry, despite its delayed adoption of the concept of safety climate, a previous study by Gillen *et al.* (2013) has been explored to enhance its understanding and improve workers' safety and health. Moreover, previous systematic reviews have been conducted to evaluate traditional safety management approaches which include active behavioral change interventions for safety (Mullan *et al.*, 2015), strategies for improving patient safety culture (Morello *et al.*, 2013), and interventions in occupational health and safety management systems (Robson *et al.*, 2007; Vitrano *et al.*, 2023).

With the advancement in digital technologies in construction, virtual reality (VR) technologies have been extensively explored in several areas to enhance safety management (Jacobsen *et al.*, 2021; Zoleykani *et al.*, 2023). Examples of these areas include workforce training, skill transfer,

health monitoring, hazard identification, etc. Chander *et al.* (2021) utilized VR to simulate specific work environments for training purposes, such as working at height, providing learners with immersive experiences that offer realistic perceptions. Adami *et al.* (2023) employed a hardware controller, specifically the HTC Vive controller, to facilitate interaction between research interviewees and employees from the virtual industry through VR-based training. As for skill transfer, VR supports the transfer of complex skills and knowledge by offering realistic and interactive simulations that allow workers to practice and refine their abilities in a virtual environment. Moreover, Adami *et al.* (2021) incorporated a VR treadmill to achieve the function of artificial intelligence (AI) navigation and remote teleoperation. Furthermore, Huang *et al.* (2022) collected electroencephalography (EEG) data from participants undergoing VR-based training in construction safety. Their study aimed to measure the health conditions of trainees to mitigate adverse health impacts resulting from overtime work among construction workers. Another study by Wang *et al.* (2015) suggested that the use of a visual and virtual construction site can be beneficial for project managers and safety officers in identifying job hazards automatically or manually before construction begins.

Despite the useful applications of VR in construction safety management, it is still challenging for researchers and practitioners to widely adopt VR technologies, considering the vast and diverse nature of the construction industry (Li *et al.*, 2018). As such, previous studies that focused on construction workers' training through the application of VR still face various challenges. Bosché *et al.* (2016) revealed that many current VR-based construction training programs are still conducted outside the job and in off-site locations, which may lead to low effectiveness. A comparative study found that the use of PowerPoint had a similar effect on learning as VR, indicating that the value of VR is not fully recognized by some stakeholders (Leder *et al.*, 2019). Moreover, virtual experiences can have real-life consequences, as intense negative emotions experienced in virtual environments can strongly correlate with negative rumination in the real world. This refers to the occurrence of harmful thoughts related to distress that can persist beyond virtual experience (Lavoie *et al.*, 2021).

Existing review studies on the application of VR (Kim *et al.*, 2013; Wang *et al.*, 2018; Ahmed, 2019; Wen and Gheisari, 2020) have focused on specific areas (e.g., safety training, and hazard recognition) within the construction industry, which address the need for a state-of-the-art review encompassing a wider application of VR in construction safety management. Li *et al.* (2018) conducted a state-of-the-art research from 1997 to 2017 on virtual and augmented reality (VR/AR) with a particular focus on VR/AR technology characteristics, application domains, safety scenarios,

and evaluation methods. Other previous review studies on the application of VR have focused on a specific safety field within the construction industry. For example, Gao *et al.* (2019) conducted a systematic review of the effectiveness of traditional tools and computer-aided technologies (e.g., VR, AR, mixed reality, serious games, and computer-generated simulations) for health and safety training in the construction sector. Moreover, Babalola *et al.* (2023) conducted a systematic and bibliometric analysis of immersive technologies for occupational safety and health in construction from 2000 to 2021. Akindele *et al.* (2024) conducted a state-of-the-art analysis of VR applications in construction health and safety by examining published articles from 2010 to 2023. Lopez *et al.* (2022) reviewed the advancement and applications of VR systems within the construction industry, highlighting their significance in design, training, planning, and management. Man *et al.* (2024) systematically reviewed the effectiveness of VR applications in construction safety training and education, using meta-analysis techniques to synthesize data from various research studies conducted over the past decade.

Despite the valuable contributions of previous studies that have explored the broader applications of AR, VR, and mixed reality in the construction industry, critical gaps remain in the context of construction safety management. While existing research identifies various immersive technology applications and their associated challenges, there is limited focus on the current uses of VR in managing safety within construction environments. Notably, no comprehensive framework has been proposed to address the interrelationship between the current uses, challenges, and future research directions of VR applications for construction safety management. The absence of a conceptual framework for VR use in construction safety explains the complexity of the construction industry, which often involves varying conditions, a diverse array of worker demographics, and evolving safety regulations, which complicate efforts to develop generalized VR applications. Moreover, it complicates managerial efforts to implement consistent training practices and inhibits the potential for standardized safety training protocols. These knowledge gaps in extant literature would not only provide a deeper understanding of the current uses and challenges but also outline the future research directions of VR applications for construction safety management. Addressing these existing gaps is essential to advance the field and provide a foundation for developing effective strategies for VR applications for construction safety management. Therefore, this review study aims to conduct a systematic literature review on the current uses, challenges, and future research directions of VR applications for construction safety management. To achieve the overarching aim, the following specific research objectives are set:

1. Discuss the current uses of VR applications for construction safety management.
2. Identify the challenges that hinder the adoption of VR applications for construction safety

management.

3. Discuss the future research directions of VR applications for construction safety management.

By conducting this state-of-the-art review, it would provide valuable insights into the theoretical and practical implementation of VR technology in enhancing health, wellbeing, and safety in the construction industry. It also identifies and addresses the key challenges by proposing a framework highlighting future research directions of VR applications in construction safety management.

2. Research methods

This review study employed a systematic literature review to provide a comprehensive procedure for analyzing extant literature in a transparent and structured manner. The systematic literature review adopted the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher, 2009). The PRISMA guidelines outline a structured process for searching, selecting, and analyzing existing scientific literature, which ensures thoroughness and minimizes bias in the findings (Rethlefsen *et al.*, 2021). The PRISMA guidelines were selected for this review study because of their evidence-based nature, auditable steps, and well-established use in similar review studies (Moher, 2009; Regona *et al.*, 2022). The systematic literature review resulted in methodological and transparent literature assessments, allowing for an exhaustive exploration of available documents. Figure 1 shows an overview of the research methods.

<Please insert Figure 1 about here>

2.1. Search strategy

The initial step of this review is to conduct a bibliometric search in the Scopus database. The Scopus database was selected because of its comprehensive coverage of academic literature, a comprehensive collection of scholarly articles, and a wider reach in capturing relevant research (Powell and Peterson, 2017; Mongeon and Paul-Hus, 2016). Compared with other electronic databases (e.g., Web of Science), Scopus covers more recent publications and has a faster indexing process, which are crucial for a review aiming to present the latest advancements and trends (Chadegani *et al.*, 2013). Since it can provide a vast and current body of scholarly works, Scopus has been used in many previous studies (Antwi-Afari *et al.*, 2023; Jiang *et al.*, 2024; Mu and Antwi-Afari, 2024). Given the title of this review study, three primary keywords, namely “virtual reality”, “safety management”, and “construction industry”, were used in the title/abstract/keyword search in Scopus. The initial search string used in Scopus was (TITLE-ABS-KEY (virtual reality OR vr) AND TITLE-ABS-KEY (safety management) AND (TITLE-ABS-KEY (construction industry) AND DOCTYPE (all) AND ACCTYPE (all) AND PUBYEAR > 1999).

2.2. Selection criteria

After the initial search, 245 documents were retrieved, consisting of articles, books, reviews, conference papers, etc. The first selection criterion was based on the search period. In this study, the search period was defined from 2000 to 2023 (as of 20 July 2023). Next, the subject area was limited to “engineering”, thus removing documents not related to engineering fields (e.g., construction) to prevent cross-disciplinary articles. Also, only articles written in English language were included in this study. Conference papers and book chapters were excluded, while only journal articles were included in this study. This is because journal articles often provide extensive and higher-quality information than other types of publications (Butler and Visser, 2006; Jiang *et al.*, 2024; Lu and Antwi-Afari, 2024; Liu *et al.*, 2025; Tian *et al.*, 2025). Comparatively, conference papers and book chapters may have very little impact and may complicate the findings when added to journal articles when conducting literature reviews (Hosseini *et al.*, 2018). After the selection criteria, 94 articles were retained in the literature sample for further analysis.

2.3. Selection process

During the selection process, the 94 articles were carefully read and examined based on the titles, abstracts, and full texts related to the studied topic “VR applications for construction safety management”. Some articles were excluded if their contents did not specifically relate to safety management in the construction industry. For example, some previous studies (Ji *et al.*, 2023) that focused on VR applications but not specifically in the construction industry were excluded. In addition, other articles (Chan *et al.*, 2020) that focused on construction safety management but did not specifically use VR technologies were excluded. Moreover, articles (Qamsane *et al.*, 2022) that were outside the scope of VR applications for construction safety management were excluded. After the selection process, 58 articles were obtained for subsequent analyses and qualitative discussion.

2.4. Data extraction, quality assessment, and included articles

Quality assessment of individual articles was conducted by two reviewers, KW and MAA, following the inclusion and exclusion criteria. Any disagreement was resolved by consensus with a third reviewer (i.e., BOG). Articles deemed unrelated were excluded from the study. After obtaining 58 included articles, a thorough review was conducted for each article to extract data such as article title, year of publication, authors’ names, institution/affiliation, publication type, research aim, methodology, current uses, challenges, and future research directions. This systematic data extraction process enhanced the empirical rigor of reporting analytical results of

previous studies. Notably, the included sample of this review is comparable to a similar recent review study on VR for safety training (Scorgie *et al.*, 2024).

3. Results and discussion

3.1. Current uses of VR applications for construction safety management

The current uses of VR technologies for construction safety management could be classified into four main areas. They include (1) safety training and education, (2) safety risk management, (3) hazard identification, and (4) prevention through design. Figure 2 illustrates the distribution of the included articles across the four main current uses. As shown in Figure 2, safety training and education had the highest number of published articles (32 articles) that used VR technologies for construction safety management. This is followed by safety risk management (11 articles), hazard identification (8 articles), and prevention through design (7 articles).

<Please insert Figure 2 about here>

Table 1 provides an overview of the current uses of VR technologies for construction safety management during the studied period. As shown in Table 1, it summarises some of the included articles based on the current uses, types of VR technologies, and main findings. It is noteworthy that some articles (e.g., Hadikusumo and Rowlinson, 2002) were featured in both hazard identification and prevention through design sections.

<Please insert Table 1 about here>

3.1.1. Safety training and education

Safety training and education are of great importance in the management of construction safety because it has a positive effect on workers' attitudes, personality traits, work environments, and organizational cultures through knowledge enhancement. According to Ahmed (2019), safety education and training are essential for fostering a secure and healthy workplace in the construction sector. Li *et al.* (2012) also found that one of the best ways to improve construction safety management performance is through safety training. The focus on addressing construction safety training using VR is evident, with 55% of included articles, as depicted in Figure 2.

Traditional safety training methods, such as classroom instruction and on-the-job training, often lack engagement and fail to prepare employees for real-life risks. In contrast, immersive VR training allows users to practice in realistic, risk-free simulations, leading to significantly better retention and confidence in their skills (Scorgie *et al.*, 2024). Lecture-based training and VR-based training were two dominant training methods in construction safety management because of their realistic experience. Bhagwat *et al.* (2021) used a mobile-based VR system to

create a game for safety training. Using *t*-test, a statistically significant ($p \leq 0.05$) difference was found between students and construction professionals. It was reported that while construction experts chose virtual-based training due to its simplicity of use and time-saving advantages, the mobile VR module was favored by students due to its realistic and engaging experience. Similarly, Rey-Becerra *et al.* (2023) compared VR-based training and lecture-based training with different instructional techniques among construction workers in Colombia to determine their effectiveness in improving safety outcomes. Their results reported subjective enjoyment ($t[98] = -3.5, p < .001$), perceived usefulness ($t[98] = -3.1, p = .002$), and perceived difficulty ($t[98] = -2.4, p = .02$). They suggested that VR training proved to be significantly more efficacious compared to traditional lecture-based training methods in improving knowledge and attitudes, especially in short-term evaluation. Moreover, Feng *et al.* (2023) introduced a customized VR training platform designed specifically for enhancing excavation safety and recognizing potential hazards. Their proposed VR training system was subjected to a controlled experiment, where a comparison was drawn against a conventional health and safety manual. It was revealed that a significant main effect of time of measurement ($F(2,74) = 13.763, p < 0.001$) and no significant interactions between time and groups ($F(2,74) = 1.598, p = 0.209$). The findings from their study revealed that the use of VR training resulted in a noteworthy enhancement in practical skills, knowledge acquisition, and self-confidence, as evidenced by the scores obtained immediately after training. Han *et al.* (2022) utilized a combination of pre- and post-training assessments with the Mann-Whitney *U*-test and Kolmogorov-Smirnov (KS) statistics to evaluate VR and traditional construction safety training methods. The significant values from both Mann-Whitney *U* test ($p = 0.008$) and KS Statistic methods ($p = 0.006$) indicate that different safety training approaches resulted in significant variation in terms of skin resistance between the two groups. Their study contributes to a notable increase in knowledge retention and practical application among participants trained with VR compared to those who underwent conventional methods. Guo *et al.* (2024) focused on hazard identification performance and compared VR and traditional safety training modes across different learning styles. The results showed that the VR group had a higher hazard identification accuracy after training ($p = 0.000$), whereas the traditional group had a shorter time to identify hazards after training ($p = 0.007$). Their findings indicated that VR training leads to superior hazard identification abilities among construction workers regardless of their learning styles.

The integration of BIM and VR technologies was also another current use of safety training and education. Getuli *et al.* (2022) integrated BIM and VR technologies for the safety training of construction workers. A VR safety training platform proposed by Xu and Zheng (2020) consisted of 3D modelling, VR environment, and a well-designed teaching system programme. As

compared to traditional approaches, the designed platform was found to be more productive but had limitations, such as freedom of real-world movement while training, which influenced its realistic experience (Xu and Zheng, 2020). However, Adami *et al.* (2021) overcame the navigational constraint by allowing workers to move about in a virtual, dynamic building site using a VR treadmill. This technique improved the efficiency of safety instruction in the virtual world by enabling a more immersive and realistic training experience. In addition, the integration of AI with VR is also a novel insight that creates immersive, personalized training environments by leveraging run-time data collection and advanced analytics to simulate realistic construction hazards and actively adjust scenarios, reinforcing safe behaviors and correcting unsafe practices (Li *et al.* 2022). This significant advancement allows for active, personalized safety training in construction that allows run-time data from VR simulations to be automatically captured and analyzed, providing immediate, non-biased feedback to trainees and thereby enhancing their learning experience (Jacobsen *et al.*, 2022; Shayesteh *et al.*, 2023). This method not only improves hazard recognition and safe work practices but also extends its benefits to physical settings through advanced sensing systems, emphasizing data-driven, personalized training to reduce accidents (Jacobsen *et al.*, 2022). The introduction of a mixed reality-based platform that combines human–cyber–physical systems (HCPS) with IoT wearable devices also enhances training realism and interactivity by merging virtual simulation with real-time data from IoT sensors embedded in wearable devices (Dundee *et al.*, 2024). This integration enables a higher level of immersion, allowing trainees to experience and respond to realistic workplace hazards in a controlled virtual environment.

Seo *et al.* (2021) focused on a safety training system for active electronic construction work by using a VR-based experiential safety education system after analyzing existing accident cases and conducting in-depth interviews. It was reported that a VR-centered safety education system designed for workers at electrical construction sites improved their learning outcomes and offered a useful environment tailored for high-risk situations. For the precast concrete sector, Joshi *et al.* (2021) created a VR safety training module to improve workers' understanding of safety procedures and accident occurrences in the workplace. A Chi-square test results for independence of attributes indicated the acceptance of the hypothesis for VR (0.09, $p = 0.75$) and the traditional training method (0.58, $p = 0.45$). Their study revealed that VR training modules can improve knowledge retention and comprehension, increase workers' engagement, and have the potential to reduce accident exposures on construction sites. Nykänen *et al.* (2020) found the highest mean difference (5.94 vs. 3.91), suggesting that VR-based construction safety training had more substantial effects on self-assurance and safety-mindedness. Jelonek *et al.* (2022) investigated the

impact of learning effects, usability, and user experience in interactive systems, focusing on how these factors shape user performance and satisfaction over time. The authors found that VR simulation received positive ratings for attractiveness (2.06), perspicuity (1.88), efficiency (1.6), dependability (1.52), stimulation (2.21), and novelty (1.7), demonstrating that users become more familiar with a system, usability issues tend to diminish, leading to enhanced overall user experience and efficiency. Abotaleb *et al.* (2023) also explored the use of an interactive VR model and demonstrated that it enhances participants' understanding of safety protocols and improves retention of safety knowledge, thus serving as an effective tool in construction safety education. The average score of the students who attended the VR training was 28.6 out of 34, while the average score for those who received the traditional training was 24.8. Abotaleb *et al.* (2025) developed an immersive VR framework that significantly outperforms traditional teaching methods by effectively enhancing the core competencies required for compliance with international safety training certification bodies. The *t*-test results reported a *p*-value = 0.024, showing a statistically significant difference between the VR group and the control group, thus contributing to immersive learning experiences in both educational and professional contexts.

In summary, the current use of VR technologies for safety training and education includes VR technology and mobile phone games (Bhagwat *et al.*, 2021), VR technology and BIM systems (Getuli *et al.*, 2022), VR technology and 3D modelling (Xu and Zheng, 2020), and VR technology and treadmill applications (Adami *et al.*, 2021), etc. VR-based safety training and education areas are proven to be more effective and highly appreciated by workers as compared to lecture-based traditional training. Research in various construction activities, such as electrical services (Seo *et al.*, 2021) and precast concrete (Joshi *et al.*, 2021), had yielded similar results.

3.1.2. Safety risk management

Safety risk management is essential for construction safety management because it equips employees and organizations to proactively identify, evaluate, and reduce potential risks, resulting in safer workplaces, attitudes, and organizational culture. Pooladvand *et al.* (2021) proposed a VR technology to identify the risks involved in routine mobile crane lifting operations. The goal of their study was to determine whether VR technology can improve safety inspections and planning routines. The results revealed that mobile crane users' perceptions of risk and lifting procedures can be improved by using a computer game engine-created virtual job site. Fernández *et al.* (2023) examined the risks related to geotechnical drilling work and explored the applicability of VR technology in simulating immersive work environments, with a specific focus on interactions with drilling machinery. A 3D model of a geotechnical drilling machine was developed and

incorporated into a realistic VR environment. It was found that workers can engage with the virtual working environment, identify dangers, and prevent accidents by replicating machinery motions and various work team activities. Pooladvand and Hasanzadeh (2022) employed a promising neuroimaging technique (functional near-infrared spectroscopy- fNIRS) in an immersive mixed-reality environment built using VR technologies. Their study aimed to investigate alterations in individuals' cognitive responses and decision dynamics during electrical construction tasks in normal and stressful conditions. The results reported that under time pressure and cognitive load, construction workers showed increased fixation on hazards (18.47 s), elevated heart rates (up to 95.7 bpm), and higher electrodermal activity (9.82 μ S), with performance dropping by 42%, indicating heightened cognitive strain and risk compensation. These findings suggested that the use of VR technologies enabled the creation of a synchronized multi-modal mixed-reality environment, which proved valuable in simulating a high-risk electrical task. Choi *et al.* (2020) employed a VR forklift simulation model to evaluate the risk perceptions of forklift operators across various subtasks, including driving, loading, unloading, reversing, and turning. The results revealed that forklift operators are likely to experience reduced situation awareness (SA) regarding surrounding workers when performing loading or unloading tasks, level 1 SA ($F(3,76) = 6.105, p = 0.001$) and level 2 SA ($F(3,76) = 3.908, p = 0.012$), and a marginally observable difference for level 3 SA ($F(3,76) = 2.261, p = 0.088$). The findings highlighted that forklift operators' risk perceptions were influenced differently depending on the complexity of each task. A study by Hasanzadeh *et al.* (2020) monitored roofing activities using immersive mixed-reality environments and real-time tracking sensors to assess workers' perceptions of risk when using fall protection systems. The initial results showed that the LightGBM classifier achieved 70.1% accuracy based on the cognitive feature set for the 7-class classification. To improve the performance, the input data was relabeled, and three strategies were designed and tested. As a result, the combined approach (two-step ensemble classification) achieved 82.3% accuracy. The findings suggested that roofing workers tend to perceive lower risk levels when using fall protection, often leading to reckless behavior as they feel more secure. Yang and Fan (2025) evaluated the changes in safety knowledge and awareness, reporting an experimental mean of 4.05 (SD = 0.50) as compared with the control mean of 3.55 (SD = 0.55), $F(1,78) = 8.10, p = 0.006$, and partial $\eta^2 = 0.09$. The findings suggested that VR technology significantly enhances safety risk management by providing immersive, interactive training environments that improve learners' motivation and engagement.

The current uses of VR technology in construction safety risk management have yielded encouraging results. For example, previous studies that focused on crane lifting operations

(Pooladvand *et al.*, 2021), geotechnical drilling (Fernández *et al.*, 2023), and electrical construction (Pooladvand and Hasanzadeh, 2022) have contributed to safer workplaces by creating VR simulations that closely resemble real-life scenarios and providing realistic consequences for risky behaviors. Potential risks can be identified, evaluated, and eliminated by using these simulations, allowing construction personnel to gain vital experience in dealing with hazardous circumstances without placing themselves in immediate danger. With the advancement of digital technologies, there is considerable potential to improve the effectiveness of VR-based safety risk management systems in the construction industry.

3.1.3. Hazard identification

Hazard identification is one of the current uses of VR technologies for construction safety management, with 14% of the included articles, as shown in Figure 2. Shafiq and Afzal (2020) highlighted the necessity of leveraging VR technologies to enhance safety in construction, given that traditional approaches to hazard identification have proven to be ineffective. According to Li *et al.* (2012), examples of hazards prevalent in the construction industry include disassembling tower cranes before workers' departure, engaging in construction activities without proper personal protective equipment (PPE), etc.

Research efforts have been demonstrated to enhance the identification of hazards on construction sites through the analysis of workers' stride and balance, or their brain waves and heart rate (Jebelli *et al.*, 2018). Physiological responses from construction workers are collected from wearable sensing technologies such as heart rate monitors, EEG, etc. (Anwer *et al.*, 2021; Jebelli *et al.*, 2018). Jeon and Cai (2021) classified hazard-related perceptions by using EEG and VR for objective measurement of workers' cognitive responses and perceptual states in simulated hazardous environments. This approach offers significant novel insight by shifting the focus beyond traditional subjective hazard perception assessments, providing a deeper understanding of how workers neurologically process and react to potential dangers. Similarly, Jeon and Cai (2022) established correlations between EEG signals and various construction hazards by constructing EEG classifier through experiments conducted within an immersive VR setting. They simulated different types of hazards in the VR environment and collected EEG signals from participants using wearable EEG and VR devices. The results revealed that the light gradient boosting machine classifier achieves an accuracy of 70.1% based on extracted cognitive features. Their study underscores the feasibility of integrating wearable EEG and VR for distinguishing different hazards. A study by Kim *et al.* (2017) introduced a hazard avoidance system aimed at preventing accidents. The proposed system generated 95.7% accuracy based on spatial relationships with moving objects on the jobsite. It enabled workers to discern hazards by projecting augmented

hazard information onto a wearable device, thereby enhancing their ability to avoid potential risks. Another research by Eiris *et al.* (2018) proposed a method to mitigate the planar view restriction on construction sites. In their study, VR technology was used to create an enhanced 360-degree panorama of reality (PARS). It offered an accurate and immersive depiction of construction sites by finding an average of 30% of hazards displayed throughout the assessment session, facilitating effective hazard identification processes. In addition, it was found that the system operation was user-friendly and helped to identify hazards in panoramic scenes.

From a different perspective, the challenges of planar view limitations in construction sites that are posed by vision-based avoidance systems can be mitigated by integrating 4D BIM and VR technology (Afzal and Shafiq, 2021). In their study, the integration of 4D BIM and VR technology was conducted in a user-friendly manner and offered an authentic experience akin to being on an actual construction site. Their results reported an average mean of 4.3 after the safety simulation was conducted, indicating that the 4D BIM-based VR simulation not only performed much better during safety planning but also significantly aided workers in identifying hazards. Teizer *et al.* (2013) conducted a study that introduced a 3D perspective of the predominant installation of steel. The survey results revealed that visualization technology allowed workers to assume different perspectives. For example, they would replay the scene to show a greater sense of the severity of an incident, thereby demonstrating effective hazard identification and visualization. Furthermore, Azhar (2017) conducted three case studies that illustrated how 4D simulations, BIM models, and VR environments could be leveraged to identify hazards. Such an approach greatly aided in formulating and effectively conveying plans for reducing the identified hazards among construction employees. Their approach has merit of identifying hazards, particularly when contrasted with traditional 2D drawings. It was concluded that digital tools offer a close replication of real-world conditions, thus enhancing their practical impact (Azhar, 2017).

Another use of VR technologies for hazard identification in construction involves visual cues (Lucena and Saffaro, 2022). In Lucena and Saffaro's (2022) study, construction managers were required to verbally communicate the detected hazards to instructors. Their results pointed out that Simulation B (with protocol) was indeed superior to Simulation A (without protocol), and the hazard identification efficiency observed in the use of the protocol is closely associated with the sensory stimuli provided by virtual reality technology. The use of VR technology furnished them with visual cues, enhancing their intuitive ability to identify hazardous situations, thus facilitating the process of hazard detection. Similarly, Hadikusumo and Rowlinson (2002) proposed an approach encompassing a virtual walkthrough of a simulated construction site to identify hazards. Within this context, the workers undertook the task of selecting suitable precautions aimed at

preventing accidents associated with the identified hazards. Shringi *et al.* (2022) investigated the effectiveness of VR-based safety training in enhancing hazard recognition during heavy machinery operations in the construction industry. They demonstrated that VR-based training significantly improves hazard recognition and decision-making skills with an immersive VR display showing more than a 300% increase when compared to a flat-screen display. Their findings may lead to a reduction in accidents and an enhancement in safety performance on construction sites as compared to conventional methods. Raimbaud *et al.* (2021) also explored a task-centered methodology for evaluating user interactions in VR, specifically focusing on hazard identification in building environments. Their study addressed the need for systematic evaluation techniques in VR design and revealed that a task-centered approach enhances both user engagement and hazard identification performance. Specifically, they reported that there was no significant effect of the interaction technique factor on usability scores, with p -values of 0.200, 0.638, and 0.114, respectively, on a level of significance of $\alpha = 0.05$, confirming the effect of the task-centred approach on the interaction technique usability results. Zhang *et al.* (2023) reported a 33% improvement in team performance over individuals, indicating that VR-enhanced multi-role collaboration significantly improves hazard identification in crane-lift training for modular construction. Their study enabled participants to experience realistic, immersive scenarios that foster proactive recognition and mitigation of potential safety risks, thereby enhancing overall training effectiveness and on-site safety awareness.

Taken together, the use of VR technology for construction safety management has been extensively applied in hazard identification. It includes the integration of VR technology and EEG data (Jebelli *et al.*, 2018; Jeon and Cai, 2022), VR technology and vision-based hazard avoidance systems (Kim *et al.*, 2017; Eiris *et al.*, 2018), VR technology and BIM systems (Afzal and Shafiq, 2021), and VR technology and immersive exploration strategies (Lucena and Saffaro, 2022; Hadikusumo and Rowlinson, 2002), and among others.

3.1.4. Prevention through design

Construction sites are inherently characterized by dynamic work settings, rendering the procedures essential for ensuring the safety of their designs in a comprehensive and indispensable manner for preventing accidents (Côté and Beaulieu, 2019). Recently, the concept of prevention through design (PtD) or design for safety (DfS) has garnered attention, with 12% of the included articles as depicted in Figure 2. It strives to ensure that accident prevention is prioritized when developing construction designs (Manu *et al.*, 2019). It also encompasses a multifaceted terminology reflecting its comprehensive approach to integrating safety considerations into the design process (Farghaly *et al.*, 2021). Aydin and Aktaş (2020) emphasized that integrating a

well-structured VR infrastructure in architectural design education fosters a student-centered and contextual learning environment, enhances creativity and interaction, and supports prevention through design by enabling early identification and resolution of potential issues in virtual design ecosystems.

Sacks *et al.* (2015) conducted a study involving designers and builders, wherein their interaction within a virtual construction site revealed that dialogues enhance the identification and clarity of safety issues in designs. Similarly, Hadikusumo and Rowlinson (2002) introduced a design-for-safety-process (DfSP) that amalgamates VR functionalities. The introduced DfSP empowers construction practitioners to engage in a virtual environment walk-through akin to their actual construction sites. This proactive approach facilitates the identification of inherent hazards, enabling the implementation of suitable mitigating measures to prevent potential catastrophic accidents. Heydarian *et al.* (2015) compared immersive virtual environments (IVEs) with physical built environments to evaluate their effectiveness in building design and user interaction exploration. Their study reported a marginally significant effect of the number of gaming hours on participants' IVE interaction ($\beta = 0.12$, $p = 0.075$), indicating that an hour increase in gaming results in a 0.123 unit increase in participants' IVE experience. Consequently, the findings demonstrated that IVEs can closely replicate user experiences in physical environments, offering a reliable platform for early-stage design evaluation. Lin *et al.* (2018) demonstrated that the integration of BIM, game engine, and VR technologies enhances stakeholder engagement and effective communication during the design phase. Their results showed that the overall average satisfaction was 80% among the design teams and 90% among the users, indicating a slightly higher willingness by the users to use the system.

VR technology has been demonstrated to improve emotional arousal (Yilmaz Balban *et al.*, 2021), a factor that has the potential to enhance learning through the mechanism of neuroplasticity (Duman, 2004; Green and Bavelier, 2008). Patil *et al.* (2023) employed a catalog of features that either evoke or hinder emotional reactions in comparable video simulations available on a public video-sharing platform (YouTube). Their study guided in constructing VR environments for eliciting emotional arousal, thereby enhancing their learning process. It presented design insights, including the necessity to offer agency within simulations, the incorporation of nonplayer characters into scenes, and similar strategies, as means to enhance the design for safety.

Yu *et al.* (2019) focused on the integration of VR technology, BIM, wearable devices, and massive data analysis centers. Their study aimed to generate reports about dynamic safety predictions and facilitate real-time danger warnings. The proposed BIM-based intelligent site management model integrates advanced technologies such as BIM, 3D scanning, and AR/VR, which supports prevention through design by allowing for better visualization and assessment of

potential hazards during the design and planning phases. Another research conducted by Manzoor *et al.* (2021) integrated BIM and other advanced digital technologies, including global positioning system (GPS), laser scanning, sensors, and VR. The study identified diverse attitudes among construction stakeholders regarding the integration of BIM with emerging digital technologies and highlighted the perceived effectiveness and practical application of these technologies in improving safety outcomes. Their results revealed the potential of combining BIM with other digital technologies to enhance safety in high-rise construction projects. Similarly, Shafiq and Afzal (2020) demonstrated the prospective use of virtual design construction (VDC) tools such as VR, AR, BIM, and geographic information system (GIS) for enhancing construction site safety within Gulf Cooperation Council (GCC) countries. The research highlighted that the VDC tools are mostly effective for enhancing construction site safety applications, such as fall hazards. Their study also revealed that VDC technologies can significantly enhance construction safety, and these digital tools transform traditional document-oriented safety procedures into digitalized practices, enabling safety managers to virtually visualize and analyze construction sites for proactive safety measures and effective training. Shehadeh and Alshboul (2025) demonstrated that the integration of VR with advanced machine learning algorithms in engineering and architectural design proactively detects and mitigates design clashes and optimizes workflows, thereby reducing errors and iterative corrections to improve overall project safety and efficiency. In conclusion, the use of VR technology has been applied to PtD principles. This current use of VR technology can help in designers' decision-making (Sacks *et al.*, 2015; Hadikusumo and Rowlinson, 2002), leveraging VR technology to evoke emotional arousal (Yilmaz Balban *et al.*, 2021; Patil *et al.*, 2023), combining VR technology and BIM systems (Yu *et al.*, 2019; Shafiq and Afzal, 2020), and synergizing VR technology and GPS technology (Manzoor *et al.*, 2021), etc.

3.2. Challenges to the adoption of VR applications for construction safety management

Despite the usefulness of VR technologies, some challenges are hindering their adoption in the construction industry. This section discusses five main challenges of VR applications for construction safety management.

3.2.1. Technology (Software and Hardware)

One of the challenges hindering the adoption of VR applications for construction safety management is the lack of technology, including both software and hardware components. The software components used in VR applications include rendering engines, 3D modelling software, spatial computing libraries, and interactive development environments. Some of the hardware components used in VR applications in the construction industry include head-mounted displays

(HMDs), motion tracking sensors, haptic devices, and data gloves (Wang *et al.*, 2018). Each of these elements contributes to creating a seamless and IVE for construction safety management applications. Additionally, there is a shortage of experts who are well-versed in VR applications for construction safety management, further complicating this challenge. Despite the crucial role that technology plays in enhancing safety performance within the construction sector, Pham *et al.* (2018) underscore the limited emphasis on safety within mainstream higher education curricula. As a result, there is a shortage of technology experts with an understanding of construction safety management, which hinders resolving existing problems related to VR applications. Jawalkar (2024) identified the delicate balance required between enhancing device performance and software demands needed to achieve seamless AI integration and real-time interaction in VR applications to create more intuitive and immersive user experiences as another challenge. On the other hand, the cost of hardware VR technology, such as motion tracking sensors, haptic devices, and data gloves and the lack of standardization and knowledge on how to use these VR technologies are some of the major challenges facing VR applications in construction safety management (Dela Cruz and Dajac, 2021). Jeon and Cai (2022) explored the feasibility of classifying different types of hazards based on a multi-class EEG classifier that was developed in a VR environment. While EEG signals provide useful data patterns for achieving ubiquitous hazard identification, the primary impediment lies in their constrained proven ability to effectively distinguish hazard types such as falls, slip/trip incidents, and struck-by occurrences. Insufficient information is available, which consequently leads to less effective feedback for workers at risk (Brehaut *et al.*, 2016).

3.2.2. Social acceptance

Lack of social acceptance is another challenge facing VR applications for construction safety management. According to Xu and Zheng (2020), the absence of practical training in safety management is often responsible for avoidable incidents in the construction industry. They emphasized that by raising awareness of construction workers' safety knowledge, VR-based technologies can considerably reduce the occurrence of accidents on construction sites. However, the lack of acceptance of VR technology by construction workers and practitioners has led to slow progress in VR applications for construction safety management.

Moreover, subjective measurements are not beneficial to effective VR applications for construction safety management. As such, objective resource tracking and self-assessment methods need to be aligned with common data standards. Wolf *et al.* (2022) reported that there exists a scarcity of construction safety research dedicated to the generation and analysis of intrinsic data derived from trainees' actions within the virtual environment. These authors

examined how performance analysis in a virtual environment can provide accurate feedback to heighten workers' behavior, leading to improved practices during real-world tasks. Their study also outlines future research directions for enhancing construction safety education, emphasizing the correlation between objective tracking data and self-assessment.

3.2.3. Cultural influence

Cultural factors also have adverse impacts on the use of VR technology for construction safety management. They include experience, age, and education of VR technology users. VR users of relatively lower educational backgrounds tend to slow the implementation of VR technologies. Rey-Becerra *et al.* (2023) stated that although VR-based training is more effective than lecture-based training, it is important to consider the characteristics of the workers to ensure its effectiveness when designing a training program with virtual technologies. For instance, research has indicated that trainees with higher levels of education tend to achieve better training outcomes compared to those with lower levels of education (Rey-Becerra *et al.*, 2023). Their findings indicated that trainees with higher levels of education tend to achieve better training outcomes compared to those with lower levels of education.

VR users of relatively harder-to-be emotional arousal tend to show lower effectiveness of VR applications. However, emotional arousal is hard to consider in prevention through design principles. Within the context of construction management, Bhandari and Hallowell (2017) identified that the hyper-realistic reenactment of typical workplace injuries can evoke specific emotional responses among construction workers. The elicitation of these emotions not only enhances learning outcomes (Bhandari *et al.*, 2019) but also influences risk-taking behavior (Tixier *et al.*, 2019). Nonetheless, the logistical complexities tied to crafting hyper-realistic re-creations pose challenges in implementing such replications across diverse sectors of the industry in a cost-efficient manner. Consequently, integrating emotional arousal into the design for construction safety raises the emotions of the hardly-rouse users, aiming to heighten construction workers' awareness of on-site risks.

3.2.4. Risk compensation

Despite substantial efforts by researchers to mitigate workplace risks over the past decades, the high number of work incidents occurring annually indicates that many interventions for safety and enhancements in technology have not been fully realized. This observation raises the potential for a hidden negative effect of security precautions, referred to as risk compensation.

Pooladvand and Hasanzadeh (2022) conducted a study on electrical construction tasks by employing VR and fNIRS neuroimaging. They reported that workers experienced difficulties in

processing nearby physical information because of a lack of cognitive resources, resulting in the misperception of facing time constraints and greater mental demands. These cognitive failures caused by risk compensation may lead to a heightened dependence on safety protections and increased at-risk decisions, ultimately causing a decline in safety performance. Similarly, Hasanzadeh *et al.* (2020) created an immersive mixed-reality environment that combines VR technology and passive haptics for roofing tasks. They assessed the participants' behavioral reactions as they performed roofing tasks in the mixed-reality simulation under three different levels of safety protection. The results showed that providing more safety interventions gave participants a false sense of invulnerability, leading to a 55% increase in risk-taking behavior, including getting closer to the roof edge, leaning over it, and spending more time exposed to the risk of falling (Hasanzadeh *et al.*, 2020). The studies offered empirical insights into how increased safety protections could inadvertently signal workers to take additional risks, demonstrating the phenomenon of risk compensation.

3.2.5. Cost-effectiveness

High implementation costs can hinder the widespread use of VR technologies. According to Xu and Zheng (2020), although traditional safety education techniques such as lectures, presentations, and video training are cost-effective, they may not encourage employee involvement and knowledge retention. Similarly, the implementation of VR applications may pose financial challenges due to the high costs associated with procuring and setting up the necessary hardware (Halbig *et al.*, 2022). VR training cost is attributed to hardware procurement (VR headsets), software development, and the creation of custom VR modules tailored to specific training objectives, while the cost of traditional training methods involves venue rentals, instructor fees, printed materials, and physical training props. Additionally, the uniqueness and complexity of construction projects make it challenging to replicate construction site experiences in a virtual environment, which can impact the cost and development time. The difficulty in simulating a real construction site may lead to a lesser sense of presence and feeling of realism in a virtual construction site, affecting the cost-effectiveness of the technology.

3.3. Future research directions of VR applications for construction safety management

Figure 3 presents the interrelationships between the current uses, challenges, and future research directions of VR applications for construction safety management. Within each of the five main challenges of VR for construction safety management, specific challenges were identified and may serve as focal points for future research directions. Each specific challenge inherently gives

rise to corresponding future research directions, thereby establishing a direct relationship that drives the advancement of VR applications for construction safety management.

<Please insert Figure 3 about here>

3.3.1. Research focus on technology development

It is suggested that further studies should focus on VR technology development, including software and hardware technologies. In terms of software technology, researchers, practitioners, and policymakers should invest more resources in training personnel on VR applications in construction safety management. Regarding hardware technology, the innovation and upgrading of VR technologies should be accelerated to meet industry needs. For example, Kim *et al.*, (2018) explored the accuracy and robustness of current mapping technologies such as simultaneous localization and mapping (SLAM). It was found to be ineffective when tested in challenging environments. To allow the augmentation and visualization of the dynamic nature of the construction environment, VR technologies that can continuously collect and update real-world conditions should be tested in future research.

3.3.2. Increase in users' social acceptance of VR applications

In addition to technological constraints, Yung and Khoo-Lattimore (2017) stated that societies' and users' resistance to accepting a virtual alternative also poses a challenge for VR applications. Therefore, future research is recommended to discuss how to increase the level of awareness and practical implications of VR applications in construction safety management. The level of importance and awareness should be conducted in future studies among various stakeholders such as construction workers, practitioners, policymakers, the public, etc. By increasing the social acceptance of VR technologies, more users would be interested in conducting theoretical and practical research into VR applications in construction, thus enhancing their safety, wellbeing, and health. Moreover, to leverage the importance of VR technologies for construction safety management, it is crucial to adopt objective methods for evaluating their effectiveness in future studies. Previous studies have adopted traditional approaches to assessing the usefulness and implementation of VR technologies (Adami *et al.*, 2023; Rey-Becerra *et al.*, 2023). Rey-Becerra *et al.* (2023) evaluated training outcomes of workers based on self-reports. Similarly, Adami *et al.* (2023) adopted two self-assessment surveys to evaluate participants' trust in the robot and their self-efficacy in operating the robot. The surveys were used to assess participants' perceptions and confidence in interacting with the robotic system during the VR-based training. Despite their usefulness, surveys may lead to bias and inaccuracies because they are subjective. Due to these limitations, objective methods of assessing VR-based technologies are needed in the construction industry. In addition, data collected from surveys may not be effective for determining

relationships among participants. Therefore, to enhance the effectiveness of VR technologies for construction safety management, future studies should incorporate objective measurements such as cue utilization, tracking systems or sensors (Neuhausen *et al.*, 2020; Wang *et al.*, 2020), and accident reports to assess organizational outcomes (Rey-Becerra *et al.*, 2023). These objective VR technology measurements can provide more accurate and reliable data that can improve workers' safety knowledge, behavior, and overall safety performance. Therefore, future studies should embrace objective measurements to assess the efficacy of VR applications for construction safety management.

3.3.3. Addressing cultural considerations related to VR applications

Since cultural factors have a greater impact on VR users, future research should explore the relationships between different cultural factors (experience, age, education, etc.). As Rey-Becerra *et al.* (2023) pointed out a positive correlation between education levels and training outcomes. However, there are notable research gaps in the understanding of cultural factors influencing the effectiveness of VR-based safety training. Future studies should address these gaps before unequivocally recommending cultural factors for inclusion in safety training programs. One research gap is the cultural variances in learning styles. The existing literature may not adequately address how cultural differences impact learning styles and preferences in the context of VR-based safety training. Research should explore how cultural backgrounds influence individuals' receptiveness to VR technology and the most effective instructional methods across diverse cultural settings. Another research gap is the cultural sensitivity in VR content. Current studies may not sufficiently consider the cultural sensitivity of VR content in safety training modules. Future research should investigate how cultural nuances and values influence the design of VR scenarios, ensuring that content is relatable and resonates with users from different cultural backgrounds. A third research gap is the impact of cultural diversity on knowledge retention. Research has yet to comprehensively explore how cultural diversity within VR training groups affects knowledge retention and the application of safety protocols. Future studies should investigate whether diverse cultural compositions influence the effectiveness of safety training outcomes and the long-term retention of learned information. Furthermore, developing a safety culture that emphasizes the significance of responsible behavior even in virtual environments can aid in the reduction of risk compensation tendencies. Finally, while existing research hints at the efficacy of VR-based emotional engagement in safety training, there is a need for cross-cultural validation. Future studies should assess whether emotional engagement strategies in VR are universally effective or if cultural variations influence their impact on safety learning outcomes.

The results of such studies could help identify the most effective VR-based safety training strategies across diverse cultural settings.

3.3.4. Minimize the negative impact of risk compensation

Further discussion is required on how to effectively employ VR technology in construction safety management while minimizing the negative impact of risk compensation. According to Hasanzadeh *et al.* (2020), there is a lack of empirical evidence of safety measures that are potential subjects of risk compensation in the construction industry and more safety precautions may implicitly encourage employees to take more risks, which may result in risk compensation. While previous studies have discussed the concept of risk compensation and its impact on safety behaviors in various settings, there is a notable paucity of studies investigating construction worker engagement in risk-compensatory behaviors. The author showed the need to discover how the construction sector develops and implements safety solutions to help counteract the effects of risk compensation. Designing VR simulations that closely imitate real-life circumstances, deliver realistic repercussions for risky behaviors, and include training modules could address risk perception and improve decision-making processes. There is a need to conduct longitudinal studies to track the long-term effects of safety interventions on workers' risk-taking behavior. This would provide a more comprehensive understanding of how risk compensation evolves and its impact on injury occurrences. Also, developing and utilizing objective measurement tools to assess risk-taking behavior on construction sites. This would involve the use of advanced technologies for real-time monitoring and analysis of workers' behaviors in response to varying levels of safety interventions. Ongoing research and collaboration among experts in VR technology, risk management, and occupational safety would be critical in creating complete answers to this dilemma.

3.3.5. Reduce the cost of VR technologies

The high cost of VR technologies is one of the hindrances to improving construction safety management. Halbig *et al.* (2022) reported the concerns raised about the cost of VR technologies. The cost of acquiring and installing VR hardware may be prohibitive, rendering the envisioned software platform undesirable to certain consumers. Hilfert and König (2016) pointed out that the widespread VR applications will greatly affect the cost of VR technologies. One approach to reducing the cost of VR technologies is to use open-source VR software and hardware platforms that are freely available to researchers and developers. These platforms provide a cost-effective way to develop and test VR applications without the need for expensive proprietary software and hardware. Another approach is to use cloud-based VR platforms that allow researchers to create

and deliver VR applications over the internet. Cloud-based VR platforms can reduce the cost of VR technology by eliminating the need for expensive hardware and software installations. Also, continued research into software optimization can lead to more efficient utilization of hardware resources, allowing VR applications to run on less powerful and therefore more affordable hardware. This can include improvements in rendering techniques, compression algorithms for audio and visual data, and streamlining of VR software development processes. Therefore, it is recommended that future research should discuss how to reduce the cost of VR applications while taking into account their quality so that they can be used more widely.

4. Conclusion

This review study aims to conduct a systematic literature review of the current uses, challenges, and future research directions of VR applications for construction safety management. Through a systematic literature review by following the PRISMA guidelines, this study comprehensively evaluated the research landscape regarding VR applications for construction safety management. The results indicated a noticeable rise in research interest concerning VR applications for construction safety management, with four current uses such as: (1) safety training and education (55%), (2) safety risk management (19%), (3) hazard identification (14%), and (4) prevention through design (12%). Besides, the challenges of VR technology adoption for construction safety management include technology (software and hardware), social acceptance, cultural influences, risk compensation, and cost-effectiveness. Importantly, the review study proposed a framework showing the interrelationships as well as outlining the future research directions. They include (1) research focus on technology development, (2) increase in users' social acceptance of VR applications, (3) addressing cultural considerations related to VR applications, (4) minimize the negative impact of risk compensation, and (5) reduce the cost of VR technologies.

The findings from this review contribute significantly to the advancement of VR technology applications within construction safety management. These findings carry significant implications for safety training practices, educational program development, and economic sustainability in the construction industry. First, IVEs have proven to be effective in enhancing PtD through hazard recognition, situational awareness, and real-time decision-making. The findings identified the need for VR simulations to do more than train for compliance, but also condition participants through consequence-driven modules that mirror real-life hazards. Future VR-based safety programs should therefore incorporate realistic feedback loops and risk perception elements to discourage over-reliance on safety equipment and promote intrinsic hazard awareness. Second, VR training programs should also be culturally and educationally structured to ensure inclusivity and to optimize knowledge retention across diverse worker populations. A critical gap identified in this

paper is the limited presence of VR and safety management content within higher education curricula. Without targeted capacity-building in educational institutions, the widespread deployment of VR in the construction industry is likely to remain constrained. Academic institutions must therefore embed modules that combine digital innovation with occupational safety practices, equipping future professionals with the skills to develop, deploy, and evaluate VR safety solutions. Third, this paper underscored cost as a persistent barrier to the adoption of VR technologies. The future directions outlined viable cost-reduction pathways, notably, the use of open-source platforms and cloud-based VR applications could eliminate software licensing and reduce local hardware demands. Additionally, the reusability, scalability, and automation potential of VR simulations could enable cost-efficient alternatives over time. Reductions in workplace incidents as facilitated by effective VR training could translate into lower insurance premium, fewer absenteeism, and enhanced project continuity, which collectively yield substantial long-term savings.

Nonetheless, this study has limitations. The research methods were limited to journal articles available in the Scopus database and published in English, which may have resulted in the omission of pertinent articles from other databases like Web of Science or those published in different languages. Moreover, the conceptual framework was developed without empirical data, thereby relying solely on existing literature. Therefore, future research could benefit from incorporating diverse databases and multilingual articles to obtain a more holistic understanding of the field. Also, future research should empirically validate the proposed framework using a mixed-methods approach, incorporating case studies, experiments, surveys, and hypothesis development to rigorously assess its practical effectiveness. Additionally, expanding the circulation of this research can foster greater collaboration and discussion on the applications of VR in construction safety management, enhancing its relevance and impact across various contexts.

Data Availability Statement

All raw data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations of Interest

None

References

Abotaleb, I., Hosny, O., Nassar, K., Bader, S., Elrifae, M., Ibrahim, S., El Hakim, Y. and Sherif, M. (2023), "An interactive virtual reality model for enhancing safety training in construction education", *Computer Applications in Engineering Education*, Vol. 31, No. 2, pp.324-345, doi: <https://doi.org/10.1002/cae.22585>.

- Abotaleb, I.S., Elhakim, Y., El Riface, M., Bader, S., Hosny, O., Abodonya, A., Ibrahim, S., Sherif, M., Sorour, A. and Soliman, M. (2025), "A framework to integrate virtual reality into international standard safety trainings", *Engineering, Construction and Architectural Management*, Vol. 32, No. 4, pp. 2320-2341, doi: <https://doi.org/10.1108/ECAM-09-2023-0969>.
- Adami, P., Rodrigues, P.B., Woods, P.J., Becerik-Gerber, B., Soibelman, L., Copur-Gencturk, Y. and Lucas, G. (2021), "Effectiveness of VR-based training on improving construction workers' knowledge, skills, and safety behavior in robotic teleoperation", *Advanced Engineering Informatics*, Vol. 50, pp. 101431, doi: <https://doi.org/10.1016/j.aei.2021.101431>.
- Adami, P., Singh, R., Borges Rodrigues, P., Becerik-Gerber, B., Soibelman, L., Copur-Gencturk, Y. and Lucas, G. (2023), "Participants matter: effectiveness of VR-based training on the knowledge, trust in the robot, and self-efficacy of construction workers and university students", *Advanced Engineering Informatics*, Vol. 55, pp. 101837, doi: <https://doi.org/10.1016/j.aei.2022.101837>.
- Afzal, M. and Shafiq, M.T. (2021), "Evaluating 4D-BIM and VR for effective safety communication and training: a case study of multilingual construction job-site crew", *Buildings*, Vol. 11, No. 8, pp. 319, doi: <https://doi.org/10.3390/buildings11080319>.
- Ahmed, S. (2019), "A review on using opportunities of augmented reality and virtual reality in construction project management", *Organization, Technology and Management in Construction: An International Journal*, Vol. 11, No. 1, pp. 1839–1852, doi: <https://doi.org/10.2478/otmcj-2018-0012>.
- Akindele, N., Taiwo, R., Sarvari, H., Oluleye, B., Awodele, I. A. and Olaniran, T. O. (2024), "A state-of-the-art analysis of virtual reality applications in construction health and safety", *Results in Engineering*, Vol. 23, pp. 102382, doi: <https://doi.org/10.1016/j.rineng.2024.102382>.
- Antwi-Afari, M. F., Li, H., Chan, A. H. S., Seo, J., Anwer, S., Mi, H. Y., Wu, Z., and Wong, A. Y. L. (2023), "A science mapping-based review of work-related musculoskeletal disorders among construction workers", *Journal of Safety Research*, Vol. 85, pp. 114-128, doi: <https://doi.org/10.1016/j.jsr.2023.01.011>.
- Anwer, S., Li, H., Antwi-Afari, M. F., Umer, W., and Wong, A. L. Y. (2021), "Evaluation of physiological metrics as a real-time measurement of physical fatigue in construction workers: state-of-the-art review", *ASCE, Journal of Construction Engineering and Management*, Vol. 147, No. 5, pp. 03121001, doi: [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0002038](https://doi.org/10.1061/(ASCE)CO.1943-7862.0002038).
- Aydin, S., and Aktaş, B. (2020), "Developing an integrated VR infrastructure in architectural design education", *Frontiers in Robotics and AI*, Vol. 7, pp. 495468, doi: <https://doi.org/10.3389/frobt.2020.495468>.
- Azhar, S. (2017), "Role of visualization technologies in safety planning and management at construction jobsites", *Procedia Engineering*, Vol. 171, pp. 215–226, doi: <https://doi.org/10.1016/j.proeng.2017.01.329>.
- Babalola, A., Manu, P., Cheung, C., Yunusa-Kaltungo, A. and Bartolo, P. (2023), "A systematic review of the application of immersive technologies for safety and health management in the construction sector", *Journal of Safety Research*, Vol. 85, pp. 66–85, doi: <https://doi.org/10.1016/j.jsr.2023.01.007>.
- Bhagwat, K., Kumar, P. and Delhi, V.S.K. (2021), "Usability of visualization platform-based safety training and assessment modules for engineering students and construction professionals", *Journal of Civil Engineering Education*, Vol. 147, No. 2, pp. 04020016, doi: [https://doi.org/10.1061/\(ASCE\)EI.2643-9115.0000034](https://doi.org/10.1061/(ASCE)EI.2643-9115.0000034).
- Bhandari, S. and Hollowell, M.R. (2017), "Emotional engagement in safety training: impact of naturalistic injury simulations on the emotional state of construction workers", *Journal of Construction Engineering and Management*, Vol. 143, No. 12, pp. 04017090, doi: [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0001405](https://doi.org/10.1061/(ASCE)CO.1943-7862.0001405).
- Bhandari, S., Hollowell, M.R. and Correll, J. (2019), "Making construction safety training interesting: a field-based quasi-experiment to test the relationship between emotional arousal and situational interest among adult learners", *Safety Science*, Vol. 117, pp. 58–70, doi: <https://doi.org/10.1016/j.ssci.2019.03.028>.
- Bosché, F., Abdel-Wahab, M. and Carozza, L. (2016), "Towards a mixed reality system for construction trade training", *Journal of Computing in Civil Engineering*, Vol. 30, No. 2, pp. 04015016, doi: [https://doi.org/10.1061/\(ASCE\)CP.1943-5487.0000479](https://doi.org/10.1061/(ASCE)CP.1943-5487.0000479).
- Brehaut, J. C., Colquhoun, H. L., Eva, K.W., Carroll, K., Sales, A., Michie, S., Ivers, N. and Grimshaw, J. M. (2016), "Practice feedback interventions: 15 suggestions for optimizing effectiveness", *Annals of Internal Medicine*, Vol. 164, No. 6, pp. 435, doi: <https://doi.org/10.7326/M15-2248>.
- Butler, L. and Visser, M. S. (2006), "Extending citation analysis to non-source items", *Scientometrics*, Vol. 66, No. 2, pp. 327–343, doi: <https://doi.org/10.1007/s11192-006-0024-1>.
- Chadegani, A. A., H. Salehi, M. M. Yunus, H. Farhadi, M. Fooladi, M. Farhadi, and N. A. Ebrahim. (2013), "A comparison between two main academic literature collections: Web of Science and Scopus Databases," Vol. 9, No. 5, pp.18- 26, doi: <https://doi.org/10.5539/ass.v9n5p18>.
- Chan, K., Louis, J. and Albert, A. (2020), "Incorporating worker awareness in the generation of hazard proximity warnings", *Sensors*, Vol. 20, No. 3, pp. 806, doi: <https://doi.org/10.3390/s20030806>.
- Chander, H., Shojaei, A., Deb, S., Kodithuwakku Arachchige, S.N.K., Hudson, C., Knight, A.C. and Carruth, D.W. (2021), "Impact of virtual reality-generated construction environments at different heights on postural

- stability and fall risk”, *Workplace Health & Safety*, Vol. 69, No. 1, pp. 32–40, doi: <https://doi.org/10.1177/2165079920934000>.
- Cheng, T. and Teizer, J. (2013), “Real-time resource location data collection and visualization technology for construction safety and activity monitoring applications”, *Automation in Construction*, Vol. 34, pp. 3–15, doi: <https://doi.org/10.1016/j.autcon.2012.10.017>.
- Choi, M., Ahn, S., and Seo, J. O. (2020), “VR-based investigation of forklift operator situation awareness for preventing collision accidents”, *Accident Analysis and Prevention*, Vol. 136, pp. 105404, doi: <https://doi.org/10.1016/j.aap.2019.105404>.
- Côté, S. and Beaulieu, O. (2019), “VR road and construction site safety conceptual modeling based on hand gestures”, *Frontiers in Robotics and AI*, Vol. 6, pp. 15, doi: <https://doi.org/10.3389/frobt.2019.00015>.
- Dela Cruz, O.G. and Dajac, J. S. (2021), “Virtual reality (VR): a review on its application in construction safety”, *Turkish Journal of Computer and Mathematics Education*, Vol. 12, No. 11, pp. 3379–3393. Available via: <https://www.proquest.com/scholarly-journals/virtual-reality-vr-review-on-application/docview/262392280/se-2?accountid=15390> (Accessed on: September 22, 2024).
- Dudhee, V., Bandara, P. D., Vukovic, V., Nalakath, A., Bass, P. and Bass, E. (2024), “Artificial intelligence-enhanced virtual reality for health and safety training in construction”. Available via: https://ceur-ws.org/Vol-3938/Paper_8.pdf.
- Duman, R.S. (2004), “Neural plasticity: consequences of stress and actions of antidepressant treatment”, *Dialogues in Clinical Neuroscience*, Vol. 6, No. 2, pp. 157–169, doi: <https://doi.org/10.31887/DCNS.2004.6.2/rduman>.
- Eiris, R., Gheisari, M. and Esmacili, B. (2018), “PARS: Using augmented 360-degree panoramas of reality for construction safety training”, *International Journal of Environmental Research and Public Health*, Vol. 15, No. 11, pp. 2452, doi: <https://doi.org/10.3390/ijerph15112452>.
- Farghaly, K., Collinge, W., Mosleh, M. H., Manu, P. and Cheung, C. M. (2021), “Digital information technologies for prevention through design (PtD): a literature review and directions for future research”, *Construction Innovation*, Vol. 22, No. 4, pp. 1036–1058, doi: <https://doi.org/10.1108/CI-02-2021-0027>.
- Feng, Z., Lovreglio, R., Yiu, T.W., Acosta, D.M., Sun, B. and Li, N. (2023), “Immersive virtual reality training for excavation safety and hazard identification”, *Smart and Sustainable Built Environment*, Vol. 13, No. 4, pp. 883–907, doi: <https://doi.org/10.1108/SASBE-10-2022-0235>.
- Fernández, A., Muñoz-La Rivera, F. and Mora-Serrano, J. (2023), “Virtual reality training for occupational risk prevention: application case in geotechnical drilling works”, *International Journal of Computational Methods and Experimental Measurements*, Vol. 11, No. 1, pp. 55–63, doi: <https://doi.org/10.18280/ijcmem.110107>.
- Gao, Y., Gonzalez, V.A. and Yiu, T.W. (2019), “The effectiveness of traditional tools and computer-aided technologies for health and safety training in the construction sector: A systematic review”, *Computers & Education*, Vol. 138, pp. 101–115, doi: <https://doi.org/10.1016/j.compedu.2019.05.003>.
- Getuli, V., Capone, P., Bruttini, A. and Sorbi, T. (2022), “A smart objects library for BIM-based construction site and emergency management to support mobile VR safety training experiences”, *Construction Innovation*, Vol. 22, No. 3, pp. 504–530, doi: <https://doi.org/10.1108/CI-04-2021-0062>.
- Gillen, M., Schneider, S. and Goldenhar, L. (2013), *Safety culture and climate in construction: Bridging the gap between research and Practice, Safety Culture and Climate in Construction: Bridging the Gap Between Research and Practice*. CPWR - The Center for Construction Research and Training. Available via: <https://www.elcosh.org/document/3782/d001295/Safety%2BCulture%2Band%2BClimate%2Bin%2BConstruction%253A%2BBridging%2Bthe%2BGap%2BBetween%2BResearch%2Band%2BPractice.html> (Accessed: 26 June 2023).
- Green, C.S. and Bavelier, D. (2008), “Exercising your brain: A review of human brain plasticity and training-induced learning”, *Psychology and Aging*, Vol. 23, No. 4, pp. 692–701, doi: <https://doi.org/10.1037/a0014345>.
- Guo, X., Liu, Y., Tan, Y., Xia, Z., and Fu, H. (2024), “Hazard identification performance comparison between virtual reality and traditional construction safety training modes for different learning style individuals”, *Safety Science*, Vol. 180, pp. 106644, doi: <https://doi.org/10.1016/j.ssci.2024.106644>.
- Hadikusumo, B.H.W. and Rowlinson, S. (2002), “Integration of virtually real construction model and design-for-safety-process database”, *Automation in Construction*, Vol. 11, No. 5, pp. 501–509, doi: [https://doi.org/10.1016/S0926-5805\(01\)00061-9](https://doi.org/10.1016/S0926-5805(01)00061-9).
- Halbig, A., Babu, S.K., Gatter, S., Latoschik, M.E., Bruckamp, K. and Von Mammen, S. (2022), “Opportunities and challenges of virtual reality in healthcare – a domain experts inquiry”, *Frontiers in Virtual Reality*, Vol. 3, pp. 837616, doi: <https://doi.org/10.3389/frvir.2022.837616>.
- Han, Y., Yang, J., Diao, Y., Jin, R., Guo, B., and Adamu, Z. (2022), “Process and outcome-based evaluation between virtual reality-driven and traditional construction safety training”, *Advanced Engineering Informatics*, Vol. 52, pp. 101634, doi: <https://doi.org/10.1016/j.aei.2022.101634>.

- Hasanzadeh, S. and de la Garza, J.M. (2020), "Productivity-safety model: debunking the myth of the productivity-safety divide through a mixed-reality residential roofing task", *Journal of Construction Engineering and Management*, Vol. 146, No. 11, pp. 04020124, doi: [https://doi.org/10.1061/\(asce\)co.1943-7862.0001916](https://doi.org/10.1061/(asce)co.1943-7862.0001916).
- Hasanzadeh, S., De La Garza, J.M. and Geller, E.S. (2020), "Latent Effect of Safety Interventions", *Journal of Construction Engineering and Management*, Vol. 146, No. 5, pp. 04020033, doi: [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0001812](https://doi.org/10.1061/(ASCE)CO.1943-7862.0001812).
- Heydarian, A., Carneiro, J.P., Gerber, D., Becerik-Gerber, B., Hayes, T. and Wood, W. (2015), "Immersive virtual environments versus physical built environments: A benchmarking study for building design and user-built environment explorations", *Automation in Construction*, Vol. 54, pp. 116–126, doi: <https://doi.org/10.1016/j.autcon.2015.03.020>.
- Hilfert, T. and König, M. (2016), "Low-cost virtual reality environment for engineering and construction", *Visualization in Engineering*, Vol. 4, No. 1, pp. 2, doi: <https://doi.org/10.1186/s40327-015-0031-5>.
- Hosseini, M.R., Martek, I., Zavadskas, E.K., Aibinu, A.A., Arashpour, M. and Chileshe, N. (2018), "Critical evaluation of off-site construction research: a scientometric analysis", *Automation in Construction*, Vol. 87, pp. 235–247, doi: <https://doi.org/10.1016/j.autcon.2017.12.002>.
- Huang, D., Wang, X., Liu, J., Li, J. and Tang, W. (2022), "Virtual reality safety training using deep EEG-net and physiology data", *The Visual Computer*, Vol. 38, No. 4, pp. 1195–1207, doi: <https://doi.org/10.1007/s00371-021-02140-3>.
- Jacobsen, E.L., Solberg, A., Golovina, O. and Teizer, J. (2022), "Active personalized construction safety training using run-time data collection in physical and virtual reality work environments", *Construction Innovation*, Vol. 22, No. 3, pp.531-553, doi: <https://doi.org/10.1108/CI-06-2021-0113>.
- Jawalkar, S. K. (2024), "Enhancing AR/VR hardware: innovations in user-friendly wearable technologies and AI integration", *International Journal of Multidisciplinary Research and Growth Evaluation*, Vol. 5, No. 3, pp. 994-997, doi: <https://doi.org/10.54660/IJMRGE.2024.5.3.994-997>.
- Jebelli, H., Hwang, S. and Lee, S. (2018), "EEG signal-processing framework to obtain high-quality brain waves from an off-the-shelf wearable EEG device", *Journal of Computing in Civil Engineering*, Vol. 32, No. 1, pp. 04017070, doi: [https://doi.org/10.1061/\(ASCE\)CP.1943-5487.0000719](https://doi.org/10.1061/(ASCE)CP.1943-5487.0000719).
- Jelonek, M., Fiala, E., Herrmann, T., Teizer, J., Embers, S., König, M. and Mathis, A. (2022), "Evaluating virtual reality simulations for construction safety training: a user study exploring learning effects, usability and user experience", *i-com*, Vol. 21, No. 2, pp. 269-281, doi: <https://doi.org/10.1515/icom-2022-0006>.
- Jeon, J. and Cai, H. (2021), "Classification of construction hazard-related perceptions using: Wearable electroencephalogram and virtual reality", *Automation in Construction*, Vol. 132, pp. 103975, doi: <https://doi.org/10.1016/j.autcon.2021.103975>.
- Jeon, J. and Cai, H. (2022), "Multi-class classification of construction hazards via cognitive states assessment using wearable EEG", *Advanced Engineering Informatics*, Vol. 53, pp. 101646, doi: <https://doi.org/10.1016/j.aei.2022.101646>.
- Ji, Y., Wang, Y., Zhao, H., Gui, G., Gacanin, H., Sari, H. and Adachi, F. (2023), "Multi-agent reinforcement learning resources allocation method using dueling double deep Q-network in vehicular networks", *IEEE Transactions on Vehicular Technology*, pp. 1–15, doi: <https://doi.org/10.1109/TVT.2023.3275546>.
- Jiang, Q., Antwi-Afari, M.F., Fadaie, S., Mi, H.-Y., Anwer, S. and Liu, J. (2024), "Self-powered wearable Internet of Things sensors for human-machine interfaces: a systematic literature review and science mapping analysis", *Nano Energy*, Vol. 131, 110252, doi: <https://doi.org/10.1016/j.nanoen.2024.110252>.
- Joshi, S., Hamilton, M., Warren, R., Faucett, D., Tian, W., Wang, Y. and Ma, J. (2021), "Implementing virtual reality technology for safety training in the precast/ prestressed concrete industry", *Applied Ergonomics*, Vol. 90, pp. 103286, doi: <https://doi.org/10.1016/j.apergo.2020.103286>.
- Kim, K., Kim, H. and Kim, H. (2017), "Image-based construction hazard avoidance system using augmented reality in wearable device", *Automation in Construction*, Vol. 83, pp. 390–403, doi: <https://doi.org/10.1016/j.autcon.2017.06.014>.
- Kim, M., Wang, X., Love, P., Li, H. and Kang, S.-C. (2013), "Virtual reality for the built environment: a critical review of recent advances", *Journal of Information Technology in Construction*, Vol. 18, pp. 279–305, doi: <https://www.itcon.org/2013/14>.
- Kim, P., Chen, J. and Cho, Y. K. (2018), "SLAM-driven robotic mapping and registration of 3D point clouds", *Automation in Construction*, Vol. 89, pp. 38–48, doi: <https://doi.org/10.1016/j.autcon.2018.01.009>.
- Lavoie, R., Main, K., King, C. and King, D. (2021), "Virtual experience, real consequences: the potential negative emotional consequences of virtual reality gameplay", *Virtual Reality*, Vol. 25, No. 1, pp. 69–81, doi: <https://doi.org/10.1007/s10055-020-00440-y>.
- Leder, J., Horlitz, T., Puschmann, P., Wittstock, V. and Schütz, A. (2019), "Comparing immersive virtual reality and powerpoint as methods for delivering safety training: Impacts on risk perception, learning, and decision making", *Safety Science*, Vol. 111, pp. 271–286, doi: <https://doi.org/10.1016/j.ssci.2018.07.021>.

- Li, C. H. J., Liang, V., Chow, Y. T. H., Ng, H. Y. and Li, S. P. (2022), "A mixed reality-based platform towards human-cyber-physical systems with IoT wearable device for occupational safety and health training", *Applied Sciences*, Vol. 12, No. 23, pp. 12009, doi: <https://doi.org/10.3390/app122312009>.
- Li, H., Chan, G. and Skitmore, M. (2012), "Multiuser virtual safety training system for tower crane dismantlement", *Journal of Computing in Civil Engineering*, Vol. 26, No. 5, pp. 638–647, doi: [https://doi.org/10.1061/\(ASCE\)CP.1943-5487.0000170](https://doi.org/10.1061/(ASCE)CP.1943-5487.0000170).
- Li, M., Hasemi, Y., Nozoe, Y. and Nagasawa, M. (2021), "Study on strategy for fire safety planning based on local resident cooperation in a preserved historical mountain village in Japan", *International Journal of Disaster Risk Reduction*, Vol. 56, pp. 102081, doi: <https://doi.org/10.1016/j.ijdrr.2021.102081>.
- Li, X., Yi, W., Chi, H.-L., Wang, X. and Chan, A.P.C. (2018), "A critical review of virtual and augmented reality (VR/AR) applications in construction safety", *Automation in Construction*, Vol. 86, pp. 150–162, doi: <https://doi.org/10.1016/j.autcon.2017.11.003>.
- Lin, Y. C., Chen, Y.P., Yien, H. W., Huang, C. Y. and Su, Y. C. (2018), "Integrated BIM, game engine and VR technologies for healthcare design: a case study in cancer hospital", *Advanced Engineering Informatics*, Vol. 36, pp.130-145, doi: <https://doi.org/10.1016/j.aei.2018.03.005>.
- Liu, X., Antwi-Afari, M. F., Li, J., Zhang, Y. and Manu, P. (2025), "BIM, IoT, and GIS integration in construction resource monitoring", *Automation in Construction*, Vol. 174, pp. 106149, doi: <https://doi.org/10.1016/j.autcon.2025.106149>.
- Lopez, J., Bhandari, S. and Hallowell, M.R. (2022), "Virtual reality and construction industry: review of current state-of-practice and future applications", In *Construction Research Congress 2022*, pp. 174-184).
- Lu, M. and Antwi-Afari, M.F. (2024), "A scientometric analysis and critical review of digital twin applications in project operation and maintenance", *Engineering Construction and Architectural Management*, Vol. ahead-of-print No. ahead-of-print, doi: <https://doi.org/10.1108/ECAM-03-2024-0304>.
- Lucena, A. F. E. and Saffaro, F. A. (2022), "Guidelines for exploring construction sites in virtual reality environments for hazard identification", *International Journal of Occupational Safety and Ergonomics*, Vol. 28, No. 1, pp. 86–95, doi: <https://doi.org/10.1080/10803548.2020.1728951>.
- Man, S.S., Wen, H. and So, B.C.L. (2024), "Are virtual reality applications effective for construction safety training and education? A systematic review and meta-analysis", *Journal of Safety Research*, 88, pp.230-243, doi: <https://doi.org/10.1016/j.jsr.2023.11.011>.
- Manu, P., Poghosyan, A., Mahamadu, A.-M., Mahdjoubi, L., Gibb, A., Behm, M. and Akinade, O. O. (2019), "Design for occupational safety and health: key attributes for organisational capability", *Engineering, Construction and Architectural Management*, Vol. 26, No. 11, pp. 2614–2636, doi: <https://doi.org/10.1108/ECAM-09-2018-0389>.
- Manzoor, B., Othman, I., Pomares, J.C. and Chong, H.-Y. (2021), "A research framework of mitigating construction accidents in high-rise building projects via integrating building information modeling with emerging digital technologies", *Applied Sciences*, Vol. 11, No. 18, pp. 8359, doi: <https://doi.org/10.3390/app11188359>.
- Moher, D. (2009), "Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement", *Annals of Internal Medicine*, Vol. 151, No. 4, pp. 264, doi: <https://doi.org/10.7326/0003-4819-151-4-200908180-00135>.
- Mongeon, P. and Paul-Hus, A. (2016), "The journal coverage of Web of Science and Scopus: a comparative analysis", *Scientometrics*, Vol. 106, No. 1, pp. 213–228, doi: <https://doi.org/10.1007/s11192-015-1765-5>.
- Morello, R.T., Lowthian, J.A., Barker, A.L., McGinnes, R., Dunt, D. and Brand, C. (2013) "Strategies for improving patient safety culture in hospitals: a systematic review", *BMJ Quality & Safety*, Vol. 22, No. 1, pp. 11–18, doi: <https://doi.org/10.1136/bmjqs-2011-000582>.
- Mu, X. and Antwi-Afari, M. F. (2024), "The applications of Internet of Things (IoTs) in industrial management: a science mapping review", *International Journal of Production Research*, Vol. 62, No. 5, pp. 1928-1952, doi: <https://doi.org/10.1080/00207543.2023.2290229>.
- Mullan, B., Smith, L., Sainsbury, K., Allom, V., Paterson, H. and Lopez, A.-L. (2015), "Active behaviour change safety interventions in the construction industry: a systematic review", *Safety Science*, Vol. 79, pp. 139–148, doi: <https://doi.org/10.1016/j.ssci.2015.06.004>.
- Neuhausen, M., Herbers, P. and König, M. (2020), "Using synthetic data to improve and evaluate the tracking performance of construction workers on site", *Applied Sciences*, Vol. 10, No. 14, pp. 4948, doi: <https://doi.org/10.3390/app10144948>.
- Nykänen, M., Puro, V., Tiikkaja, M., Kannisto, H., Lantto, E., Simpura, F., Uusitalo, J., Lukander, K., Räsänen, T., Heikkilä, T. and Teperi, A.-M. (2020), "Implementing and evaluating novel safety training methods for construction sector workers: results of a randomized controlled trial", *Journal of Safety Research*, Vol. 75, pp. 205–221, doi: <https://doi.org/10.1016/j.jsr.2020.09.015>.
- Patil, K. R., Bhandari, S., Agrawal, A., Ayer, S. K., Perry, L. A. and Hallowell, M. R. (2023), "Analysis of YouTube comments to inform the design of virtual reality training simulations to target emotional arousal",

- Journal of Construction Engineering and Management*, Vol. 149, No. 9, pp. 04023077, doi: <https://doi.org/10.1061/JCEMD4.COENG-13245>.
- Pham, H., Dao, N.-N., Kim, J.-U., Cho, S. and Park, C.-S. (2018), "Energy-efficient learning system using web-based panoramic virtual photoreality for interactive construction safety education", *Sustainability*, Vol. 10, No. 7, pp. 2262, doi: <https://doi.org/10.3390/su10072262>.
- Pooladvand, S. and Hasanzadeh, S. (2022), "Neurophysiological evaluation of workers' decision dynamics under time pressure and increased mental demand", *Automation in Construction*, Vol. 141, pp. 104437, doi: <https://doi.org/10.1016/j.autcon.2022.104437>.
- Pooladvand, S., Taghaddos, H., Eslami, A., Nekouvaght Tak, A. and Hermann, U. (Rick) (2021), "Evaluating mobile crane lift operations using an interactive virtual reality system", *Journal of Construction Engineering and Management*, Vol. 147, No. 11, pp. 04021154, doi: [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0002177](https://doi.org/10.1061/(ASCE)CO.1943-7862.0002177).
- Powell, K.R. and Peterson, S.R. (2017), "Coverage and quality: a comparison of Web of Science and Scopus databases for reporting faculty nursing publication metrics", *Nursing Outlook*, Vol. 65, No. 5, pp. 572–578, doi: <https://doi.org/10.1016/j.outlook.2017.03.004>.
- Qamsane, Y., Phillips, J.R., Savaglio, C., Warner, D., James, S.C. and Barton, K. (2022), "Open process automation- and digital twin-based performance monitoring of a process manufacturing system", *IEEE Access*, Vol. 10, pp. 60823–60835, doi: <https://doi.org/10.1109/ACCESS.2022.3179982>.
- Raimbaud, P., Lou, R., Danglade, F., Figueroa, P., Hernandez, J.T. and Merienne, F. (2021), "A task-centred methodology to evaluate the design of virtual reality user interactions: a case study on hazard identification", *Buildings*, Vol. 11, No. 7, pp. 277, doi: <https://doi.org/10.3390/buildings11070277>.
- Reason, J. (1998), "Achieving a safe culture: theory and practice", *Work & Stress*, Vol. 12, No. 3, pp. 293–306, doi: <https://doi.org/10.1080/02678379808256868>.
- Regona, M., Yigitcanlar, T., Xia, B. and Li, R. Y. M. (2022), "Opportunities and adoption challenges of AI in the construction industry: a PRISMA review", *Journal of Open Innovation: Technology, Market, and Complexity*, Vol. 8, No. 1, pp. 45, doi: <https://doi.org/10.3390/joitmc8010045>.
- Rethlefsen, M. L., Kirtley, S., Waffenschmidt, S., Ayala, A. P., Moher, D., Page, M. J. and Koffel, J. B. (2021), "PRISMA-S: an extension to the PRISMA statement for reporting literature searches in systematic reviews", *Systematic Reviews*, Vol. 10, pp. 1–19, doi: <https://doi.org/10.1186/s13643-020-01542-z>.
- Rey-Becerra, E., Barrero, L.H., Ellegast, R. and Kluge, A. (2023), "Improvement of short-term outcomes with VR-based safety training for work at heights", *Applied Ergonomics*, Vol. 112, pp. 104077, doi: <https://doi.org/10.1016/j.apergo.2023.104077>.
- Robson, L.S., Clarke, J.A., Cullen, K., Bielecky, A., Severin, C., Bigelow, P.L., Irvin, E., Culyer, A. and Mahood, Q. (2007), "The effectiveness of occupational health and safety management system interventions: a systematic review", *Safety Science*, Vol. 45, No. 3, pp. 329–353, doi: <https://doi.org/10.1016/j.ssci.2006.07.003>.
- Sacks, R., Whyte, J., Swissa, D., Raviv, G., Zhou, W. and Shapira, A. (2015), "Safety by design: dialogues between designers and builders using virtual reality", *Construction Management and Economics*, Vol. 33, No. 1, pp. 55–72, doi: <https://doi.org/10.1080/01446193.2015.1029504>.
- Scorgie, D., Feng, Z., Paes, D., Parisi, F., Yiu, T.W. and Lovreglio, R. (2024), "Virtual reality for safety training: A systematic literature review and meta-analysis", *Safety Science*, 171, pp.106372, doi: <https://doi.org/10.1016/j.ssci.2023.106372>.
- Seo, H. J., Park, G.M., Son, M. and Hong, A.-J. (2021), "Establishment of virtual-reality-based safety education and training system for safety engagement", *Education Sciences*, Vol. 11, No. 12, pp. 786, doi: <https://doi.org/10.3390/educsci11120786>.
- Shafiq, M.T. and Afzal, M. (2020), "Potential of virtual design construction technologies to improve job-site safety in gulf corporation council", *Sustainability*, Vol. 12, No. 9, pp. 3826, doi: <https://doi.org/10.3390/su12093826>.
- Shayesteh, S., Ojha, A., Liu, Y. and Jebelli, H. (2023), "Human-robot teaming in construction: Evaluative safety training through the integration of immersive technologies and wearable physiological sensing", *Safety Science*, Vol. 159, pp. 106019, doi: <https://doi.org/10.1016/j.ssci.2022.106019>.
- Shehadeh, A. and Alshboul, O. (2025), "Enhancing engineering and architectural design through virtual reality and machine learning integration", *Buildings*, Vol. 15, No. 3, pp. 328, doi: <https://doi.org/10.3390/buildings15030328>.
- Shringi, A., Arashpour, M., Golafshani, E.M., Rajabifard, A., Dwyer, T. and Li, H. (2022), "Efficiency of VR-based safety training for construction equipment: hazard recognition in heavy machinery operations", *Buildings*, Vol. 12, No. 12, pp. 2084, doi: <https://doi.org/10.3390/buildings12122084>.
- Teizer, J., Cheng, T. and Fang, Y. (2013), "Location tracking and data visualization technology to advance construction ironworkers' education and training in safety and productivity", *Automation in Construction*, Vol. 35, pp. 53–68, doi: <https://doi.org/10.1016/j.autcon.2013.03.004>.

- Tian, Y., Antwi-Afari, M. F., Seo, J., Mi, H.-Y. and Fidaie, S. (2025), "A systematic review of human-autonomy teams in project management", *International Journal of Building Pathology and Adaptation*, Vol. ahead-of-print, No. ahead-of-print, doi: <https://doi.org/10.1108/IJBPA-12-2024-0271>.
- Tixier, A.J.-P., Hallowell, M.R., Albert, A., Van Boven, L. and Kleiner, B.M. (2014), "Psychological antecedents of risk-taking behavior in construction", *Journal of Construction Engineering and Management*, Vol. 140, No. 11, pp. 04014052, doi: [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0000894](https://doi.org/10.1061/(ASCE)CO.1943-7862.0000894).
- U.S. Bureau of Labor Statistics (2022), *Census of fatal occupational injuries summary, 2021 - 2021 A01 results*, U.S. Bureau of Labor Statistics. U.S. Available via: <https://www.bls.gov/news.release/cfoi.nr0.htm> (Accessed: 22 June 2023).
- Vitrano, G., Micheli, G. J., Guglielmi, A., De Merich, D., Pellicci, M., Urso, D., and Ipsen, C. (2023), "Sustainable occupational safety and health interventions: a study on the factors for an effective design", *Safety Science*, Vol. 166, pp. 106249, doi: <https://doi.org/10.1016/j.ssci.2023.106249>.
- Wang, P., Wu, P., Chi, H.-L. and Li, X. (2020), "Adopting lean thinking in virtual reality-based personalized operation training using value stream mapping", *Automation in Construction*, Vol. 119, pp. 103355, doi: <https://doi.org/10.1016/j.autcon.2020.103355>.
- Wang, P., Wu, P., Wang, J., Chi, H.-L. and Wang, X. (2018), "A critical review of the use of virtual reality in construction engineering education and training", *International Journal of Environmental Research and Public Health*, Vol. 15, No. 6, pp. 1204, doi: <https://doi.org/10.3390/ijerph15061204>.
- Wen, J. and Gheisari, M. (2020), "Using virtual reality to facilitate communication in the AEC domain: a systematic review", *Construction Innovation*, Vol. 20, No. 3, pp. 509-542, doi: <https://doi.org/10.1108/CI-11-2019-0122>.
- Wolf, M., Teizer, J., Wolf, B., Bükür, S. and Solberg, A. (2022), "Investigating hazard recognition in augmented virtuality for personalized feedback in construction safety education and training", *Advanced Engineering Informatics*, Vol. 51, pp. 101469, doi: <https://doi.org/10.1016/j.aei.2021.101469>.
- Xu, Z. and Zheng, N. (2020), "Incorporating virtual reality technology in safety training solution for construction site of urban cities", *Sustainability*, Vol. 13, No. 1, pp. 243, doi: <https://doi.org/10.3390/su13010243>.
- Yang, Y. F. and Fan, C. C. (2025), "Evaluating the effectiveness of virtual reality (VR) technology in safety management and educational training: an empirical study on the application and feasibility of digital training systems", *Interactive Learning Environments*, pp.1-29, doi: <https://doi.org/10.1080/10494820.2025.2454434>.
- Yilmaz Balban, M., Cafaro, E., Saue-Fletcher, L., Washington, M.J., Bijanzadeh, M., Lee, A.M., Chang, E.F. and Huberman, A.D. (2021), "Human responses to visually evoked threat", *Current Biology*, Vol. 31, No. 3, pp. 601-612.e3, doi: <https://doi.org/10.1016/j.cub.2020.11.035>.
- Yu, Z., Peng, H., Zeng, X., Sofi, M., Xing, H. and Zhou, Z. (2019), "Smarter construction site management using the latest information technology.", *Proceedings of the Institution of Civil Engineers - Civil Engineering*, Vol. 172, No. 2, pp. 89-95, doi: <https://doi.org/10.1680/jcien.18.00030>.
- Yung, R. and Khoo-Lattimore, C. (2019), "New realities: a systematic literature review on virtual reality and augmented reality in tourism research", *Current Issues in Tourism*, Vol. 22, No. 17, pp. 2056-2081, doi: <https://doi.org/10.1080/13683500.2017.1417359>.
- Zhang, Z., Wong, M. O. and Pan, W. (2023), "Virtual reality enhanced multi-role collaboration in crane-lift training for modular construction", *Automation in Construction*, Vol. 150, pp.104848, doi: <https://doi.org/10.1016/j.autcon.2023.104848>.
- Zhou, Y., Ding, L.Y. and Chen, L.J. (2013), "Application of 4D visualization technology for safety management in metro construction", *Automation in Construction*, Vol. 34, pp. 25-36, doi: <https://doi.org/10.1016/j.autcon.2012.10.011>.
- Zhou, Z., Goh, Y.M. and Li, Q. (2015), "Overview and analysis of safety management studies in the construction industry", *Safety Science*, Vol. 72, pp. 337-350, doi: <https://doi.org/10.1016/j.ssci.2014.10.006>.
- Zohar, D. (1980) "Safety climate in industrial organizations: theoretical and applied implications.", *Journal of Applied Psychology*, Vol. 65, No. 1, pp. 96-102, doi: <https://doi.org/10.1037/0021-9010.65.1.96>.
- Zoleykani, M. J., Abbasianjahromi, H., Banihashemi, S., Tabadkani, S. A. and Hajirasouli, A. (2024), "Extended reality (XR) technologies in the construction safety: systematic review and analysis", *Construction Innovation*, Vol. 24, No. 4, pp. 1137-1164, doi: <https://doi.org/10.1108/CI-05-2022-0131>.

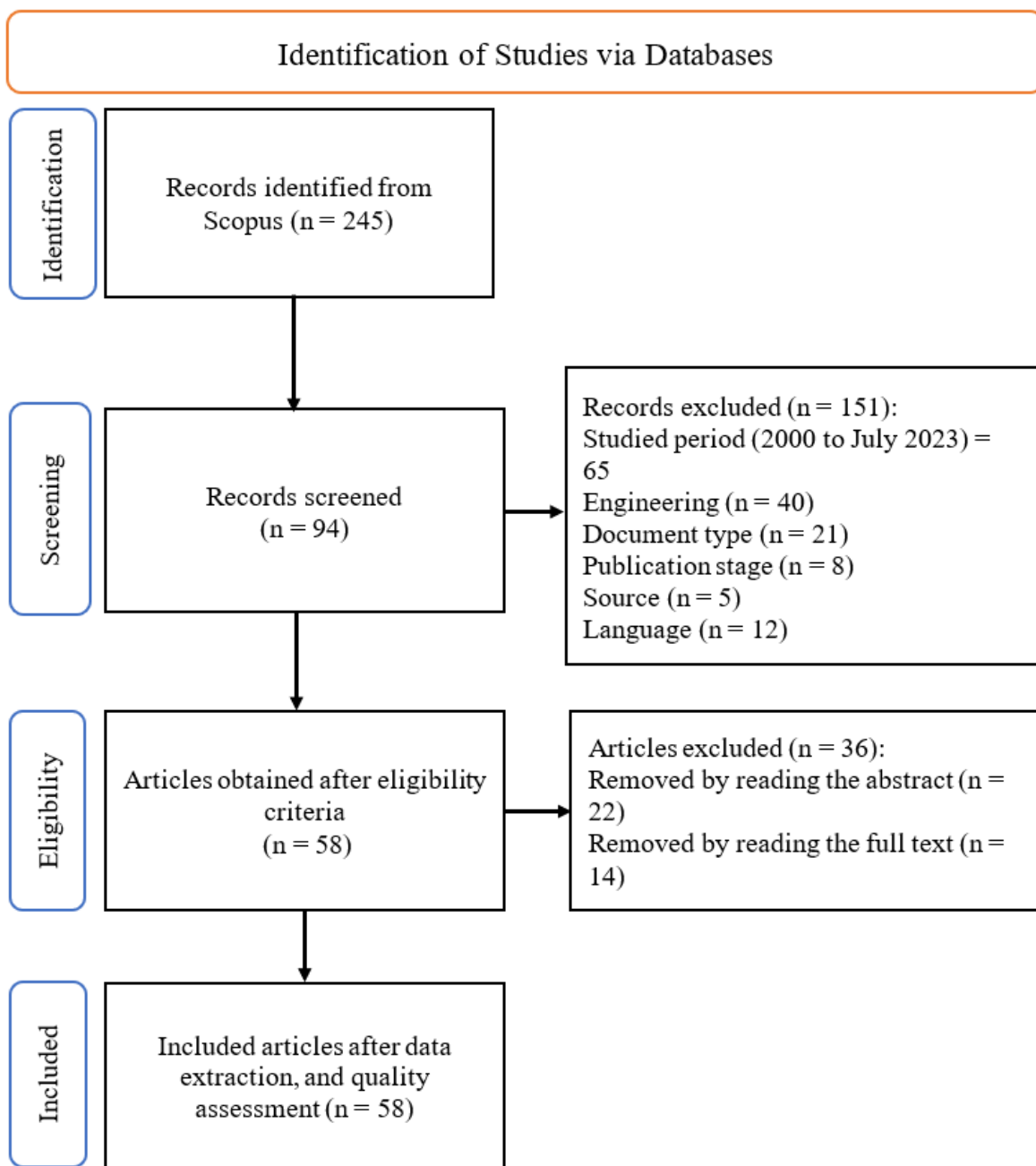


Figure 1. Overview of research methods based on PRISMA guidelines to identify included articles (Source: Authors own work)

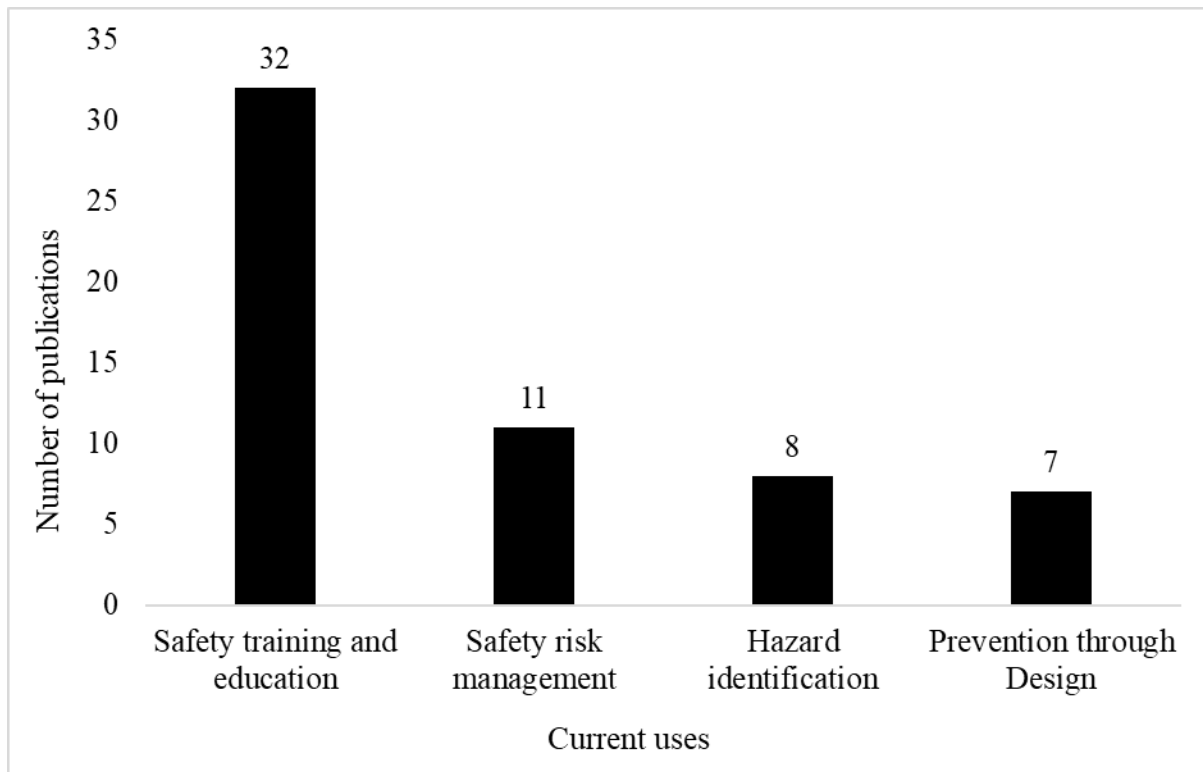


Figure 2. Distribution of published articles related to the current uses of virtual reality applications for construction safety management (Source: Authors own work)

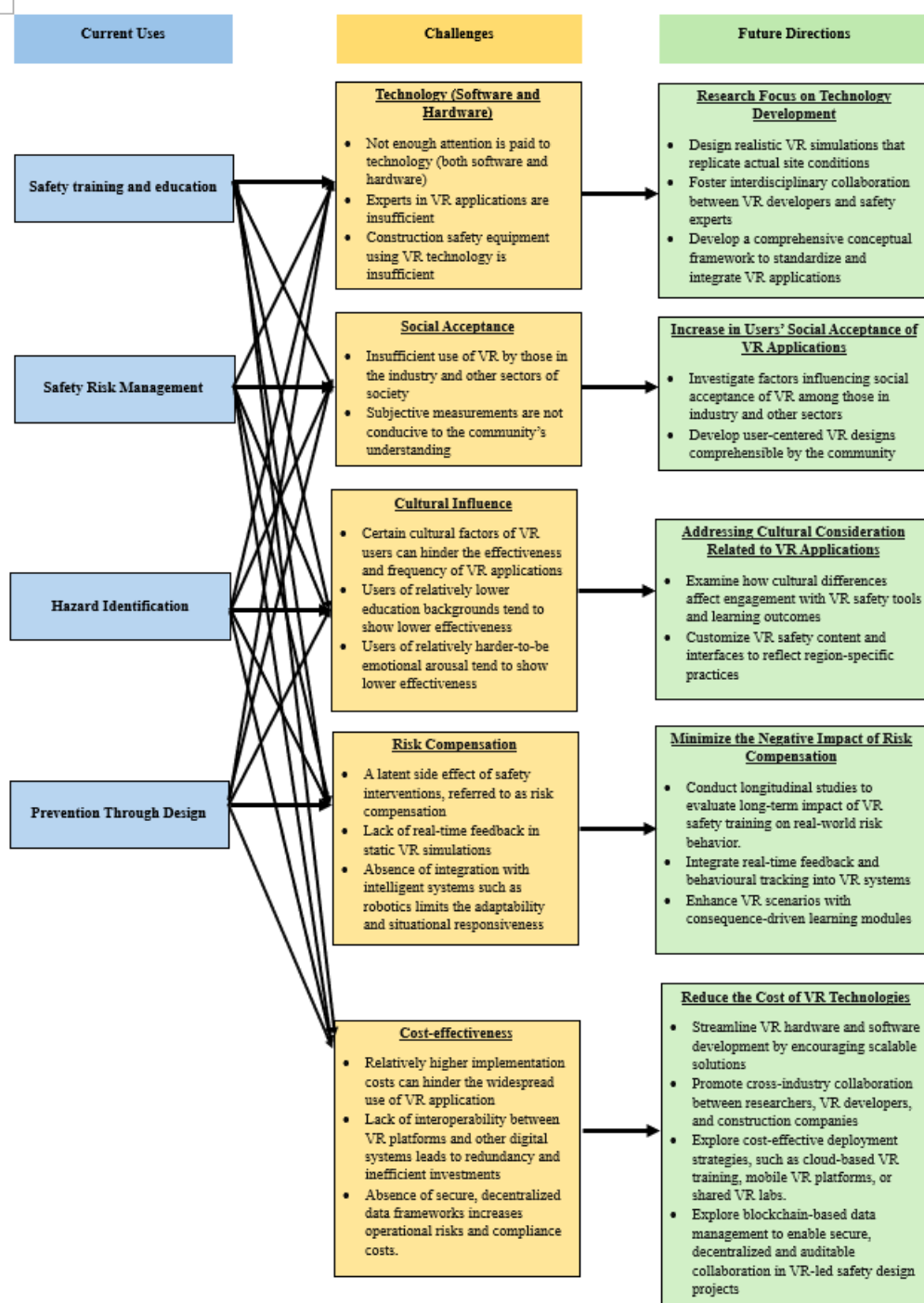


Figure 3. A framework of current uses, challenges, and future research directions of virtual reality applications for construction safety management (Source: Authors own work)

1272 **Table 1.** Summary of the current uses of VR applications for construction safety management

Current Uses	Articles	Types of VR technologies	Results and Findings	Contributions	Limitations
Safety training and education	Bhagwat et al. (2021)	Mobile virtual reality (MRV)	Create a mobile-based VR system as a game-based safety module for training. Using the <i>t</i> -test, there were statistically significant ($p \leq 0.05$) differences which existed between students and construction professionals.	The study highlights the importance of integrating digital technologies into education to enhance the learning experience through user feedback and case studies.	While the paper advocates the effectiveness of visualization platforms, it does not thoroughly evaluate potential barriers to implementation, such as cost, access to technology, and instructor training.
	Rey-Becerra et al. (2023)	VR-gamified training	Evaluate the effectiveness of a new gamified VR-based training for working at height using the Kirkpatrick model with construction workers. Results reported subjective enjoyment ($t [98] = -3.5, p < 0.001$), perceived usefulness ($t [98] = -3.1, p = 0.002$), and perceived difficulty ($t [98] = -2.4, p = 0.02$).	The paper demonstrates that VR-based safety training leads to marked improvements in short-term outcomes related to safety procedures in work environments where workers are exposed to heights.	The study faced challenges related to the fidelity of VR simulations, as real-world scenarios were difficult to fully replicate. This raised concern about the transferability of skills learned in VR to actual work environments.
	Feng et al. (2023)	VR training system	Introduce an immersive VR training system tailored for excavation	The study proposed a framework for the implementation of VR	The study highlighted a lack of long-term data to evaluate the

			safety and hazard identification. Results reveal a significant main effect of time of measurement ($F(2,74) = 13.763, p < 0.001$) and no significant interactions between time and groups ($F(2,74) = 1.598, p = 0.209$).	training systems tailored specifically to the needs of excavation workers, underlining the need for a systematic approach to safety training.	sustained impact of VR training on worker safety performance over time.
	Xu and Zheng (2020)	3D modelling virtual environment	Create a 3D modelling stage, a VR environment rendering process, and a well-designed teaching system programme. The feedback from participants revealed that the realism of the VR simulation was acceptable, with $\rho T=0.65$ and $\rho T=0.64$ for reliability.	The paper introduced a novel VR training platform that addressed the pressing need for effective safety training methods that can mitigate common hazards in urban construction sites.	The paper did not adequately address the potential challenges of implementing VR training on a large scale in the construction industry.
	Adami et al. (2021)	VR treadmill	Overcome the navigational constraint by allowing workers to move about a virtual, dynamic building site using a VR treadmill. The average gain in the VR-based training was 60.22% than in-person	The research explored the various dimensions of effective training, particularly focusing on self-efficacy, a crucial factor in successful human-robot interaction.	The research primarily focused on a single training method and did not extensively compare it with other training methods like in-person or blended approaches.

			training (39.55%). The Kappa statistics calculated were > 0.81.		
	Seo et al. (2021)	VR-based education system	Investigate the installation of a VR-based experiential safety education system in the electrical construction industry. Feedback from in-depth interviews and analyzed existing accident cases was used to develop a VR-based safety education prototype.	The paper demonstrates how VR technology can create immersive learning environments that enhance engagement and knowledge retention among participants.	The long-term effects of VR-based training on safety behavior are not thoroughly investigated in the study as it focused on immediate post-training assessments, leaving questions regarding the retention of knowledge and behavioral changes over an extended period unanswered.
	Joshi et al. (2021)	VR safety training module	Create a VR safety training module in the precast concrete sector. A Chi-square test for independence of attributes resulted in acceptance of the hypothesis for VR (0.09, p-value 0.75) and the traditional training method (0.58, p-value 0.45).	The study emphasizes increased engagement and retention rates in trainees when using immersive VR environments, which have been shown to stimulate interest and motivation in learners.	The study lacked longitudinal studies in the assessment of VR training effectiveness which poses challenges in establishing the lasting impact of VR training beyond the initial learning experience.
	Abotaleb et al. (2023)	An interactive VR model	Explored the use of an interactive VR model to	The study used the experiential learning	The study's design involved only a

			improve safety training within construction education. The average score of the students who attended the VR training was 28.6 out of 34 while the average score for those who received the traditional training was 24.8.	approach which enabled participants to develop a deeper understanding of workplace hazards and reinforce safety protocols in realistic settings, thus improving their preparedness and response to actual incidents.	one-time evaluation of the VR training sessions, implying a lack of longitudinal data on the impact of such training over time. As a result, the long-term effectiveness of VR training in enhancing safety knowledge and behavior remains uncertain.
	Jelonek et al. (2022)	VR simulations	Investigated the impact of learning effects, usability, and user experience in interactive systems, focusing on how these factors shape user performance and satisfaction over time. Results show that VR simulation had positive ratings for attractiveness (2.06), perspicuity (1.88), efficiency (1.6), dependability (1.52), stimulation (2.21), and novelty (1.7).	The study highlights the usability and user experience of VR simulations, providing empirical evidence that participants exhibited an increased sense of confidence and awareness after engaging with VR environments.	There is a need for a more extended timeframe for assessing long-term retention of knowledge gained through VR training. While immediate feedback and engagement were positively received, there is limited understanding of how well these skills translate into sustainable safe practices in actual job environments over time.
Safety risk	Pooladvand	VR framework for risk	Proposed a framework	The paper provides	The study had a

management	et al. (2021)	assessment; VR computer game	that uses VR technology to proactively assess the risks involved in routine mobile crane lifting operations. The framework was validated using two real-world lift scenarios which demonstrated measurable improvements in lift planning and risk assessment.	empirical data illustrating the effectiveness of the VR system in improving operator performance.	restricted scope for the system tested. The VR system primarily simulates specific lift operations without accounting for the variability of real-world conditions encountered on actual job sites.
	Fernández et al. (2023)	3D modelling in a VR environment	Develop 3D model of a geotechnical drilling machine and incorporate it into a realistic VR environment. This VR experience facilitated immersive interaction, enabling workers to understand processes and associated hazards, and receive immediate feedback on actions that could lead to accidents.	The study highlights that conventional safety training often adopts a generic approach, overlooking the intricate dynamics and unique hazards of geotechnical tasks.	The study relied heavily on simulated experiences, not fully replicating the unpredictability of real-world environments encountered on job sites.
	Pooladvand and Hasanzadeh (2022)	Neuroimaging technique (fNIRS) in mixed-reality environment	Employ a neuroimaging technique (functional near-infrared spectroscopy- fNIRS) in an immersive mixed-reality	The study incorporates neurophysiological measures such as EEG alongside traditional decision-making metrics which	The study was conducted in a controlled environment that may not fully replicate the complexities and

			environment built using VR technologies to investigate alterations in individuals' cognitive responses. The results indicated that under time pressure and cognitive load, construction workers showed increased fixation on hazards (18.47 s), elevated heart rates (up to 95.7 bpm), and higher electrodermal activity (9.82 μS), with performance dropping by 42%, indicating heightened cognitive strain and risk compensation.	provided a multi-faceted view of how stress and cognitive load influence dynamics, allowing for understanding of human error in high-pressure construction settings.	unpredictabilities of actual construction sites.
	Choi et al. (2020)	VR-based investigation	Forklift operators' risk perceptions were influenced differently depending on the complexity of each task. The results revealed that forklift operators are likely to experience reduced situation awareness (SA) regarding surrounding workers when	The study developed a comprehensive framework that used Virtual Reality (VR) technology to simulate real-world scenarios in which forklift operators navigate potentially hazardous environments.	While the study advocates enhanced training methodologies, the practical implications such as costs associated with implementing VR training solutions for widespread adoption in various industries remain uncertain.

			performing loading or unloading tasks , level 1 SA ($F(3,76) = 6.105, p = 0.001$) and level 2 SA ($F(3,76) = 3.908, p = 0.012$), and a marginally observable difference for level 3 SA ($F(3,76) = 2.261, p = 0.088$).		
	Hasanzadeh et al. (2020)	Productivity-Safety Model in a mixed-reality residential roofing task	Roofing workers tend to perceive lower risk levels when using fall protection, often leading to reckless behavior. The results showed that participants exposed themselves to fall risks over longer periods (Exposure duration 1 = 2.38 ± 0.59 min and Exposure duration 3 = 2.92 ± 0.88 min; $p = 0.03$).	The paper developed a mixed-reality framework that allows construction workers to engage in realistic training scenarios without the traditional risks associated with actual work environments.	The research primarily focuses on the residential roofing sector, raising questions about the generalizability of its findings to other areas of construction, such as heavy civil works or industrial construction.
Hazard identification	Jeon and Cai (2022)	Wearable EEG and Oculus Quest 2 VR headset	Establish correlations between electroencephalogram (EEG) signal patterns and various construction hazard types, constructing an EEG classifier through	This study used wearable EEG technology to monitor the brain activity of workers and derived valuable insights into how cognitive states correlate with hazard	The scope of the sample used for testing the multilevel classification model lacks diversity in terms of experience levels, roles, or even geographical settings, and the generalizability

			experiments conducted within an immersive VR setting. The initial results showed that the LightGBM classifier achieved 70.1% accuracy based on the cognitive feature set for the 7-class classification. To improve the performance, the input data was relabeled, and three strategies were designed and tested. As a result, the combined approach (two-step ensemble classification) achieved 82.3% accuracy.	perception.	of the findings was limited.
	Kim et al. (2017)	A vision-based hazard avoidance system	Introduce a vision-based hazard avoidance system aimed at accident prevention. The proposed system generated 95.7% accuracy based on spatial relationship with moving objects on the jobsite. Based on the assumption of “occlusion as true,” the accuracies were 93.81% and 66.17%,	The study introduced a prototype system that utilized real-time image processing to identify hazards and notify the user through visual cues displayed on the wearable device.	The study primarily involved a small sample size, a larger sample with diverse demographics would strengthen the validity of the findings and enhance the generalizability of the system’s effectiveness across various construction contexts.

			respectively; the assumption of “occlusion as false” resulted in 73.94% and 36.1%.		
	Eiris et al. (2018)	An augmented 360-degree panorama of reality (PARS)	Trainees found the platform has merits in learning hazard identification. Participants recognized an average of 30% of the hazards displayed throughout the entirety of the assessment session.	The study conducted rigorous evaluations and assessments, revealing that participants using the augmented 360-degree panoramas exhibit superior performance in hazard identification tasks compared to those trained with conventional methods.	The study heavily relied on technology, which may pose challenges related to scalability and implementation in workplaces where resources for augmented reality are limited.
	Afzal and Shafiq (2021)	4D building information modeling (BIM)-based VR simulation	The results showed improvement in job-site crew’s ability to recognize hazards, understand safety protocols and proactive risk response in mitigating hazards. The results revealed an average mean of 4.3 after the safety simulation was conducted, indicating that the 4D BIM-based VR simulation	The study simulated real-world scenarios, and this helped trainees visualize the complexities involved in construction sites, ultimately leading to improved comprehension of safety procedures.	The findings are largely contextualized within a specific setting, which may limit the generalizability of the results to other construction environments or geographical locations.

			performed much better during safety planning.		
	Teizer et al. (2013)	Location tracking sensors and 3D immersive data visualization	Conduct a comparable study that introduced a 3D perspective of predominant steel erection tasks. The survey results revealed that visualization technology allowed workers to assume different perspectives that in the real world they would not be able to see and being able to replay the scene creates a greater sense of the severity of an incident.	By leveraging tools such as GPS and data visualization platforms, the study presents a framework that enhances situational awareness among workers, reducing the likelihood of accidents and injuries on site.	The study heavily relied on technological infrastructure that may not be readily available on all construction sites, potentially widening the gap between those who can afford these innovations and those who cannot.
	Azhar (2017)	4D simulations, BIM models, and VR environment	Conduct three case studies that illustrated how contractors can leverage 4D simulations, BIM models, and VR environments to visually pinpoint hazards. The case studies demonstrated that BIM and VR technologies can be used as a new collaborative safety	The study's focus on the real-world application of these technologies in complex building projects provided a practical perspective that validates the theoretical framework presented and offers valuable insight into how organizations can	The study highlights a scarcity of empirical data demonstrating the long-term effects of visualization technologies on safety performance metrics in construction.

			planning, management, and training tool. Through BIM models, 4D simulations and VR environment, designers, engineers, and constructors can take effective protective measures in the project planning phase to eliminate or minimize the construction site hazards.	effectively utilize these technologies for proactive safety measures.	
	Lucena and Saffaro (2022)	VR visual cue	Introduce immersive exploration of a virtual construction site by construction managers as a means to identify and visualize potential hazards. The results pointed out that Simulation B (with protocol) was indeed superior to Simulation A (without protocol) and the hazard identification efficiency observed in the use of the protocol is closely associated with the sensory stimuli provided by virtual reality technology. The	The study outlined protocols that can significantly aid in the identification and assessment of hazards that workers may encounter on job sites.	While the paper provides a well-structured approach for using VR in construction safety training, it does not cover all possible scenarios and complexities found on varied construction sites.

			main contribution of the protocol was to induce the user to systematically reflect on the many types of hazards.		
	Hadikusumo and Rowlinson (2002)	VR virtual walkthroughs, A design-for-safety-process (DfSP)	Implement virtual walkthroughs of workers through a simulated construction site to identify hazards. The research produced a design-for-safety-process (DFSP) tool to identify safety hazards inherited during the building construction phase that are actually produced during the design phase.	The introduction of a structured approach that integrates virtually real construction models with safety processes allows stakeholders to visualize complex safety scenarios in a controlled environment.	The study relied on the assumption that construction stakeholders possess the necessary technical know-how to engage with virtually real models effectively, this could pose challenges in practical implementations where technological literacy and training may lag behind the proposed advancements.
	Raimbaud et al. (2021)	Task-centered methodology in VR environment	Explored a task-centered methodology for evaluating user interactions in VR, specifically focusing on hazard identification in building environments. There was not a significant effect of the interaction technique factor on the usability scores, with p-values of	The study emphasized the pressing need for effective and practical methods to enhance user experience and safety through improved interaction designs in VR settings.	The study had a narrow scope (the case study) which primarily focused on specific tasks related to hazard identification without addressing the broader range of possible user interactions in diverse VR applications.

			0.200, 0.638, and 0.114, respectively, on a level of significance of $\alpha=0.05$ which confirms the hypothesis about the effect of task-centred approach on the interaction technique usability results.		
	Shringi et al. (2022)	VR-based safety training	Investigated the effectiveness of VR-based safety training in enhancing hazard recognition during heavy machinery operations in the construction industry. Immersive displays were able to provide participants with sufficient depth of field to identify the distance to seemingly two-dimensional objects such as overhead electricity cables. Additionally, the identification of critical hazards improved with an immersive VR display by more than 300% when compared to that with a flat-screen	The study indicated that VR training is particularly beneficial in high-risk environments through controlled, like construction sites, where the potential for human error can lead to severe consequences.	The study may have overlooked factors such as the diversity of the workforce, including varying levels of technological proficiency among operators. Not all workers may feel comfortable navigating VR environments, which could lead to disparities in training efficacy.

			display.		
Prevention through Design	Sacks et al. (2015)	VR design decision-making	Highlight VR's utility in construction safety management, particularly its role in aiding designers' decision-making during construction execution. The results show that designers felt that their design statement overrides any safety consideration (46%) and in matters that concern decisions pertaining to construction details, the designers exhibited flexibility to changes and very high flexibility to changes was evident in design issues related to building systems details and to structural details (76% and 60%, respectively).	The study highlights how VR allows stakeholders to visualize and interact with a simulated construction environment, which enables them to identify potential hazards before actual construction begins.	The research focuses on specific contexts and may not universally apply to all types of construction environments.
	Patil et al. (2023)	VR emotional arousal	Employ opinion mining to compile a catalog of features that either evoke or hinder emotional reactions in comparable video simulations available on a public	The study analyzed feedback from users, this approach offered a novel framework for understanding how emotional engagement can enhance learning	The reliance on YouTube comments introduces potential biases, as the data collected is influenced by the nature of the comments available,

			video-sharing platform (YouTube). Results from the Valence and Arousal dimensions showed that a majority of the comments fell in the negative half of the valence dimension (Rating <0.5).	outcomes in training simulations.	which may not be representative of all users' experiences.
	Yu et al. (2019)	BIM integration with VR technologies	Concentrate on the integration of VR and augmented reality (AR) technologies with BIM, big data processing terminals, and wearable devices. The proposed BIM-based intelligent site management model integrated advanced technologies such BIM, 3D scanning, and virtual/augmented reality which supports prevention through design by allowing for better visualization and assessment of potential hazards during the design and planning phases.	The study identified key information technologies that can be integrated into construction site management practices which allow for more informed decision-making and real-time monitoring of site conditions.	The study relies heavily on case studies from specific regions, which may not universally represent the challenges and conditions encountered in other geographical contexts.
	Manzoor et al. (2021)	BIM integration with VR	Center on the fusion of BIM with advanced	The study developed a comprehensive	The study is primarily conducted within the

			digital technologies including global positioning system (GPS), laser scanning, sensors, VR, AR, and photogrammetry for the safety design of high-rise buildings. The study identified diverse attitudes among construction stakeholders regarding the integration of BIM with emerging digital technologies and highlighted the perceived effectiveness and practical application of these technologies in improving safety outcomes.	research framework that consolidates various studies to articulate measures for accident mitigation in high-rise buildings.	Malaysian context, which raises questions about the generalizability of the findings to other geographic regions with differing safety regulations, cultural factors, and construction practices.
	Shafiq and Afzal (2020)	Virtual design construction tools (e.g., BIM, GIS, VR, AR)	Demonstrate the prospective utility of virtual design construction tools such as VR, AR, BIM, and geographic information system (GIS) for enhancing construction site safety within Gulf Cooperation Council countries. The study revealed that VDC	The study conducted a comprehensive analysis of the potential benefits of VDC technologies in improving job-site safety which effectively highlighted how these technologies can facilitate better safety planning and	The study primarily addresses the challenges and perceptions of stakeholders within this geographic area, potentially restricting the applicability of their conclusions to other regions or industries.

			technologies can significantly enhance construction safety, and these digital tools transform traditional document-oriented safety procedures into digitalized practices, enabling safety managers to virtually visualize and analyze construction sites for proactive safety measures and effective training.	monitoring.	
	Heydarian et al. (2015)	Immersive virtual environments (IVEs)	Demonstrate that IVEs can closely replicate user experiences in physical environments, offering a reliable platform for early-stage design evaluation. The study found a marginally significant effect of the number of gaming hours on participants' IVE interaction ($\beta = .12$, $p = .075$); this finding indicates that one hour increase in gaming results in a 0.123 unit increase in participants'	The study's benchmarking approach, which systematically compares immersive virtual environments (IVEs) with physical environments to evaluate their effectiveness in building design and user interaction.	The study suggests a need for training programs as the potential lack of user familiarity with immersive technologies hinders effective interaction and learning outcomes.

			IVE experience scale on a 5-point Likert scale. This finding suggests that gamers think that the IVE is more similar to the physical environment than the non-gamers.		
	Lin et al. (2018)	BIM, game engine, and VR	Demonstrate that the integration of these technologies enables more effective communication during the design process. The results showed that the overall average satisfaction was 80% among the design teams and 90% among the users. The average satisfaction with the system's functions for design teams was 4.8, compared to 4.75 for the users. The average satisfaction of system's interface and willingness to utilize system for communication for the design teams was 4.25, compared to 4.75 for the users.	The study's immersive approach not only aids in identifying design flaws early in the project lifecycle but also garners valuable feedback from users, which is critical in healthcare design.	The focus on a single case study (the cancer hospital) within a specific geographical context implies that while the findings are insightful, they may not necessarily be applicable across various healthcare settings or regions with different regulations and cultural contexts.
(Source: Authors own work)					