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Review

Extended Reality (XR) Training in the Construction Industry: A Content Review

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Abstract: As modern information technology advances and equipment devices update, extended reality (XR) technologies, including virtual reality (VR), augmented reality (AR), and augmented virtuality (AV) have witnessed an increasing use and application in construction training. This review aims to comprehensively examine the evolution of XR training in the construction domain. To achieve this, a systematic literature review of 74 journal papers from the Scopus database was conducted. This paper outlines the progression of XR training from 2009 to 2023, detailing related technologies like development platforms, display devices, and input devices. The literature review reveals that XR application in construction training spans five main areas: (1) safety management, (2) skill/knowledge acquisition, (3) equipment operation, (4) human–computer collaboration, and (5) ergonomics/postural training. Additionally, this review explores the impact of trainee roles on XR training outcomes and identifies the challenges faced by XR technology in construction training applications. The findings of this literature review are hoped to assist researchers and construction engineering trainers in understanding the latest advancements and challenges in XR, thereby providing valuable insights for future research.

Keywords: extended reality (XR); virtual reality (VR); augmented reality (VR); augmented virtual reality (AV); construction training

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1. Introduction

The construction industry, often referred to as the backbone of urban development [1], necessitates a workforce with skills and adaptability to effectively navigate the intricate challenges inherent in powering social advancement [2] and achieving sustainable development goals [3,4]. Training plays a crucial role in the construction industry, serving as a vital link between theoretical knowledge and practical application. Notably, the advancements in modern information technology have facilitated the rise and widespread adoption of virtual reality (VR), augmented reality (AR), and related virtual technology in construction training [5]. Some studies also indicate that these technologies, compared to traditional training methods, enhance the effectiveness of training [6–8].

The terminology associated with virtual technologies lacks clarity in both academic and industrial contexts, encompassing terms such as virtual reality (VR), augmented reality (AR), mixed reality (MR), and extended reality (XR) [5]. For example, Wedel et al. [9] stated that MR combines VR and AR, while Zhao et al.'s literature review [10] positions MR alongside VR and AR, collectively denoted as XR. To enhance clarity and distinguish these perplexing concepts for the readers, this study incorporates the concept of a "virtuality continuum" proposed by Milgram and Kishino in 1994 [11]. As shown in Figure 1, this conceptual framework effectively distinguishes between AR, augmented virtuality (AV), and VR. Specifically, the concept of AR can be interpreted as overlaying computer-generated digital information onto the real-world environment, creating a seamless integration [12,13]. VR refers to a technology that creates computer-generated simulated environments that users can explore and interact with [13]. In addition, AV blending real-world elements into VR employs real objects as input devices for interaction within the virtual environment during construction training [14]. In this review, XR is utilized as an umbrella term encompassing virtual technologies, including VR, AR, and AV [11].

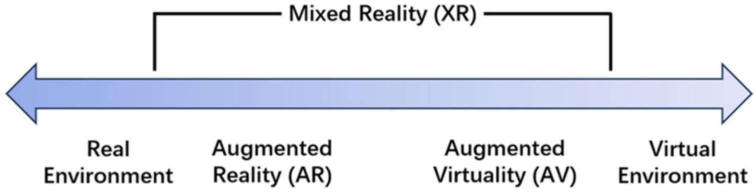

Figure 1. Reality-virtuality continuum.

The benefits of employing extended reality (XR) training in the construction industry are diverse. For example, VR simulations provide a risk-free setting for trainees to immerse themselves in realistic construction scenarios, refining their skills without compromising safety [15–17]. These technologies also facilitate collaborative training experiences, allowing professionals to participate in shared virtual environments and overcome geographical distances and disciplinary barriers [18,19]. Furthermore, VR can increase a trainees' motivation and decrease the cost compared to traditional training methods [19–21]. Additionally, AR can aid construction workers in task completion, contributing to reduced task duration and minimizing the likelihood of errors [22].

While XR training offers some advantages compared to traditional methods, it is undeniable that these technologies are still in their early developmental stages and have certain limitations. The creation of training scenarios and the achievement of realism encounters challenges. For example, current devices limit the trainee's visual perspective [23] with sensory feedback primarily focused on visual and auditory aspects, lacking tactile, olfactory, and other stimuli [24]. Additionally, developing high-quality training content demands a significant investment of both resources and time. Most VR training relies on head-mounted displays (HMD), allowing only one person to undergo training at a time, creating difficulties in scaling up simultaneous training for multiple participants on a larger scale. It is important to note that VR, AR, and AV technologies are different methods during training, although they are often grouped together. Therefore, a comprehensive literature review of XR technology in the construction field is essential. This will provide scholars and practitioners in related domains with background knowledge on XR training, enhancing their understanding of the current development status and the challenges faced in its implementation.

Furthermore, literature reviews pertaining to similar topics are also examined and evaluated in this study. It was revealed that there was a lack of research on the application of XR in the field of construction training. In terms of the review scope, certain reviews take a broader scope, offering a comprehensive examination of research within the entire architecture, engineering, and construction (AEC) field, maintaining a general focus but lacking a specific review dedicated to the construction sector [25–28]. For instance, Zhang et al. [26] utilized a mixed quantitative–qualitative review method, analyzing 206 journal articles to explore research trends and opportunities for VR application in the AEC industry. Other reviews delve into the intersection of education and construction training [29,30]. While education and construction training share a close relationship, they differ in their objectives, with education emphasizing knowledge transfer to students and focusing more on theoretical foundations, while construction training targets workers tasked with complex and hazardous construction site activities, emphasizing practical orientation. Furthermore, some reviews concentrate on construction safety training [31–34], but construction training extends beyond safety training, encompassing areas such as construction equipment operation [35]. A research gap emerges from these literature reviews, specifically the absence of a critical review focusing on XR technology in the realm of construction training.

To address the research gaps mentioned above, this review aims to provide a comprehensive overview of extended reality (XR) research pertaining to construction training, encompassing virtual reality (VR), augmented reality (AR), and augmented virtuality (AV). The specific objectives include as follows: (1) delineating the current state of development in XR training and associated technology applications; (2) examining the implementation areas of these studies within construction training; (3) investigating the influence of XR training participants on training outcomes; (4) and exploring challenges encountered in the domain of VR, AR, and AV technologies in construction training. The subsequent sections of this paper are structured as follows: Section 2 outlines the review protocol and methodology, including research questions, a systematic literature search strategy, and the data analysis of selected publications. In Section 3, the current research status of XR in construction training is provided, covering an analysis of the identified publications and specific techniques. Section 4 categorizes the application of XR in construction training. Section 5 focuses on the participants in the XR training experiments. Additionally, Section 6 delineates the challenges inherent in XR training. Finally, Section 7 concludes this literature review.

2. Review Protocol and Methodology

The literature review protocol adheres to the guidelines outlined by [36], comprising four essential phases for evaluating a quality literature review: (1) design, (2) conduct, (3) data abstraction and analysis, (4) and structuring and writing the review. As stated by Snyder [36], the design phase necessitates the formulation of a clear and well-motivated research question, followed by the selection of an appropriate review methodology tailored to the research query. It is imperative to establish a transparent search strategy, incorporating relevant search terms, explicit inclusion, and exclusion criteria. This section provides research questions to be addressed and the search strategy to be utilized, in detail.

2.1. Research Questions

As mentioned before, this paper aims to comprehensively understand the research of XR training in the construction domain. The specific research questions that this review paper intends to address are the following:

- Research Question 1 (Q1): What is the status of XR training in the construction industry?
- Research Question 2 (Q2): What are the applications of XR training in the construction industry?
- Research Question 3 (Q3): How do the participants of the XR training experiment have an impact on training results?
- Research Question 4 (Q4): What are the challenges of XR training faced in the construction industry?

2.2. Search Strategy

In this review, Scopus was utilized for literature searches, which is managed by Elsevier Publishing company and contains the metadata for over 82 million documents and more than 1.7 billion references [37]. A preliminary research search was conducted on selected sources using relevant search terms. Since this paper seeks to study the application of extended reality technology in construction training, the search terms were divided into three parts: research technology, target research areas, and target research purpose. The specific search string used to query Scopus was as follows:

TITLE-ABS (“VR” OR “virtual reality” OR “AR” OR “augmented reality” OR “XR” OR “extended reality” OR “MR”) AND TITLE-ABS (construction OR “construction site” OR “construction project” OR “construction management” OR “construction engineering” OR “construction industry”) AND TITLE-ABS (training OR “construction training” OR operation).

The initial search identified 2390 studies, which were then filtered based on publication date, with only studies published between January 2009 and December 2023 being considered. The document type was restricted to journal articles, the publication stage was final, and the language was limited to the English language. To further refine the selected articles, the study also narrowed the scope of subjects to engineering, computer science, social sciences, energy, environmental science, psychology, multidisciplinary, and decision sciences.

Following the initial screening, 506 articles were obtained. The researchers then conducted a cursory full-text reading of the 506 articles to exclude duplicates, articles outside the field of construction industry, articles irrelevant to the training, and articles where the full text was unavailable. Ultimately, a total of 74 articles were selected for an in-depth literature analysis. The database literature screening process is illustrated in Figure 2.

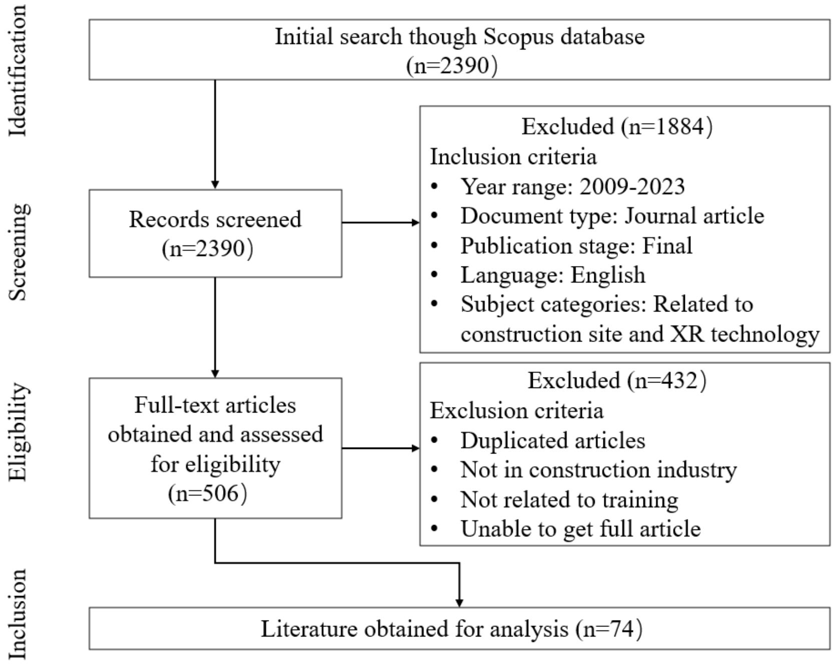

Figure 2. The literature screening process.

2.3. Data Analysis

The ultimate inclusion of 74 publications undergoes a comprehensive content review. To address the aforementioned research questions, specific data are selected from the chosen articles during the examination of their contents. The data utilized in this study are shown in Table 1.

Table 1. Data adopted for content analysis.

Data	Descriptions
Publication year	The year of publications, from 2009 to 2023
Publication source	The Journals that feature the chosen publications
Country	The first author's country where the selected publication originated
The adoption of XR technology	The XR technology employed in the selected publications, including VR, AR, AV
Keyword	The author keywords of the selected publications
XR technology	The XR technology in the selected publications, including development platforms, display devices, and input devices
XR application	Categories of XR application in construction training in the selected publications
Participants	The roles of participants in XR training experiments in the selected publications
Challenges	The challenges stated in XR training in the selected publications

3. Current Development of XR Training in Construction Industry

3.1. Overview of Identified Publications

Figure 3 illustrates the number of published articles about XR in construction training from 2009 to 2023. The trend in article publications was basically stable from 2009 to 2019, consistently featuring fewer than five articles annually. This pattern may be attributed to the construction industry's slower adoption of XR technology, trailing behind fields like manufacturing and automated driving. Commencing in 2020, a notable surge in published studies is observed, showing incremental growth throughout the years 2020 to 2023. This substantial increase is postulated to be linked to the emergence of the COVID-19 pandemic at the close of 2019. The global outbreak impacted the construction industry [38,39], disrupting normal operations and contributing to the surge in remote and online technologies, which thrived amid restrictions on large-scale offline gatherings. The escalating number of publications post-2020 underscores the sustained academic interest in investigating XR training within the construction domain.

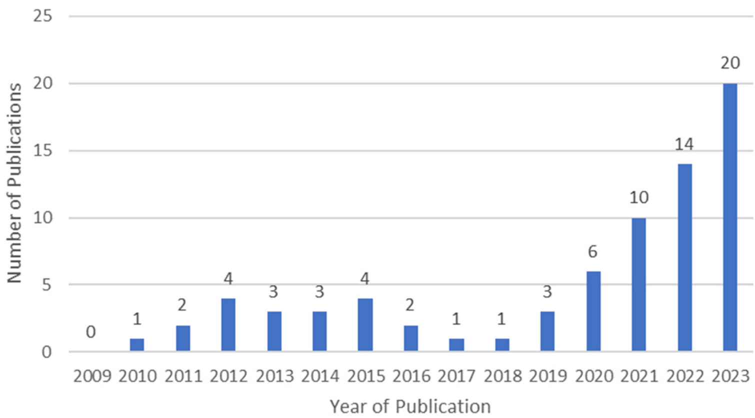

Figure 3. Number of publications from 2009 to 2023.

Table 2 presents the distribution of the 74 selected journal articles by publication source. Over 33 journals featured articles on XR technology in construction training. The top five journals, ranked by the number of selected articles, were Automation in Construction (14.9%), Journal of Computing in Civil Engineering (12.2%), Advanced Engineering Informatics (8.1%), Journal of Construction Engineering and Management (6.8%), and Safety Science (5.4%). These five journals collectively accounted for approximately half of the total selected articles. The distribution shows that most XR training articles were published in technology-related journals.

Table 2. Distribution of the selected journal articles by publication source.

Journal Title	Number of Selected Articles
Automation in Construction	11
Journal of Computing in Civil Engineering	9
Advanced Engineering Informatics	6
Journal of Construction Engineering and Management	5
Safety Science	4
Engineering, Construction, and Architectural Management	3
Construction Innovation	3
Buildings	3
Applied Sciences	2

Table 2. *Cont.*

Journal Title	Number of Selected Articles
Computer Applications in Engineering Education	2
International Journal of Computers Communications and Control	2
Sustainability	2
Accident Analysis and Prevention	2
Applied Ergonomics	1
CivilEng	1
Construction Management and Economics	1
Developments in the Built Environment	1
Education Sciences	1
Electronic Journal of Information Technology in Construction	1
i-com	1
IEEE Transactions on Learning Technologies	1
IEEE Transactions on Visualization and Computer Graphics	1
International Journal of Computational Methods and Experimental Measurements	1
International Journal of Injury Control and Safety Promotion	1
Journal of Architectural Engineering	1
Journal of Civil Engineering and Management	1
Journal of Intelligent and Robotic Systems: Theory and Applications	1
Journal of Robotics and Mechatronics	1
Journal of Safety Research	1
Journal of Surveying Engineering	1
Scientific World Journal	1
Virtual Reality	1
Visual Computer	1
Total	74

As shown in Figure 4, regarding the geographical affiliation of the first author, the United States leads with 38% of published papers. Subsequent to this, South Korea emerges as the second-highest contributor at 11%, followed by China (9%) and Australia (8%). Other countries have made comparatively modest contributions, with none exceeding three publications over the past 15 years.

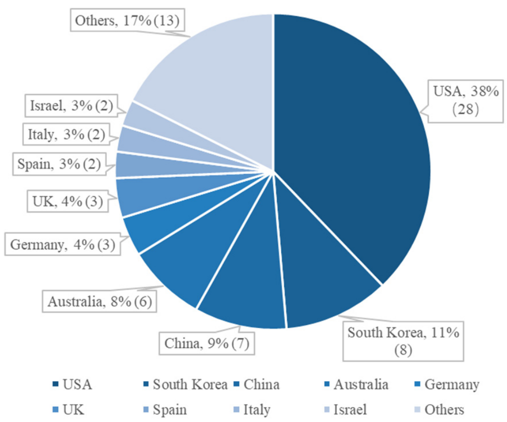

Figure 4. Distribution of publications by country.

The percentage of the research on XR technology in construction training is elucidated in Figure 5. VR technology takes the lead, constituting 89% of the applications, followed by AR at 8%, and AV at the lowest, with a mere 3%. This distribution indicates a predominant reliance on VR technology within XR applications for construction training, underscoring its substantial growth over the past 15 years.

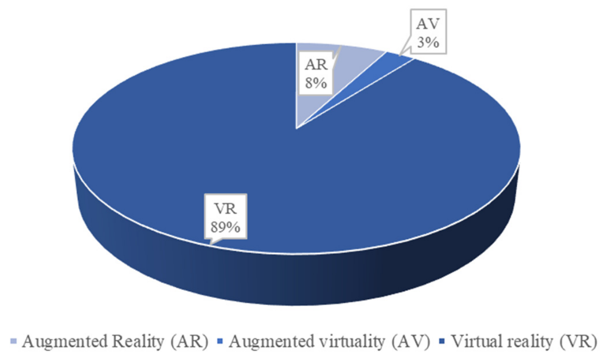

Figure 5. The percentage of VR/AR/AV applications in construction training.

Figure 6 depicts the co-occurrence network of author keywords, generated through VOSviewer 1.6.20, providing insights into the thematic content within this research domain. To improve visualization, the minimum occurrence threshold for author keywords was set to two. It is crucial to note that synonymous keywords were consolidated into representative terms. For instance, "VR" encompasses "virtual reality" and "virtual reality (VR)", and "hazard recognition" is used for both "hazard identification" and "hazard perception". After this consolidation process, 32 keywords were identified. In Figure 6, the size of the nodes corresponds to the frequency of keyword occurrences, and the thickness of the link between nodes indicates the strength of the relationship between node terms, with thicker lines representing stronger associations. Notably, XR technology in construction training emerges with the highest frequency and total link strength, prominently featuring VR. This underscores VR's widespread adoption and relative maturity in the current construction training research landscape. Apart from "VR", prevalent themes include "safety training", "construction safety", and "hazard recognition", emphasizing the collective focus on enhancing construction safety and hazard awareness. Keywords at the periphery of the network graph, such as "human–robot collaboration", "construction worker", and "user experience", although represented by smaller nodes and weaker associations, suggest potential emerging research themes that may evolve in the future and warrant attention.

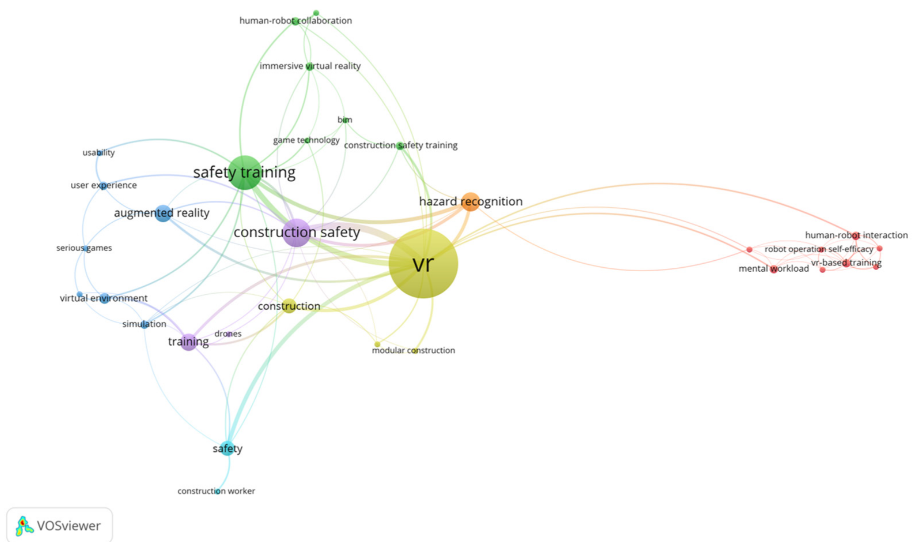

Figure 6. Author keyword co-occurrence network.

3.2. XR Training Technology

XR technology is evolving at an unprecedented rate, with tremendous benefits to the research and industry [40]. Access to new display and input devices for the consumer market, offering affordable pricing models, has accelerated the diffusion of XR technology [37]. This sub-section introduces the development platform, display device, and input device of XR technology in construction training.

3.2.1. Development Platform of XR

In the development of XR experience, a commonly employed approach involves the utilization of a game engine or a specialized development platform that has native support for XR. The game engine serves as the heart that encompasses nearly all of the functions and features required to develop a fully realized game [41,42]. It provides developers with a set of tools and functionality to assist and simplify the development, creation, and management of digital games, simulations, or other interactive applications. Modern game engines provide key features to create realistic and immersive virtual environment scenarios, including graphics rendering, physics simulation, scene graphs, audio systems, animation systems, scripting and programming interfaces, and networking functions [41,43]. For example, a graphics rendering system involves rendering objects, textures, lighting, and visual effects to enhance the fidelity of a virtual environment. In a study by Luo et al. [44], it was found that enhancing scenario fidelity significantly improves the sense of presence and usability in forklift safety training for workers. The audio system enables developers to seamlessly integrate and manage sound effects and other audio elements in construction training; Han et al. [45] introduced background sound to enhance immersion in scaffold-based safety training using VR.

Within the realm of XR training for the construction field, Unity and Unreal Engine stand out as the most widely utilized game engines. Unity3D, for example, features multi-platform system support, offering both free and commercial versions. Games developed using the Unity3D game engine can be exported as standalone applications for macOS and MS Windows, consoles such as Xbox and Wii, and smartphones running iOS, Android, Blackberry, and Windows [46]. Moreover, Unity's asset store comprises an extensive collection of images, 3D models, scripts, sound effects, and complete games, offering developers a time-saving resource [41]. Unreal Engine is renowned for its high-quality rendering effects, featuring a 64-bit color High Dynamic Range (HDR) rendering pipeline in Unreal Engine 4. This pipeline incorporates a diverse range of post-processing effects, including motion blur, depth of field, bloom, and screen space ambient occlusion [41]. In addition, both Unity and Unreal Engine have large communities; support is readily available from a diverse user base, comprising both professional and amateur developers, who actively contribute assistance in the community forums.

Other development platforms are less frequently used in the construction training field, such as WebXR, Oculus First Contact game, Second Life, and Torque 3D engine. WebXR, based on WebGL, enables the creation of XR experiences accessible through web browsers [47]. This approach allows trainees to access simulations with minimal hardware requirements. Dhalmahapatra et al. [48] employed the Oculus First Contact game to instruct users in comprehending the sequence of electric overhead crane operations and addressing potential hazards during work. Users can utilize the Oculus controllers to interact with the virtual agent within the environment. Second Life is not a game or game engine; it is a massive multiplayer 3D virtual world designed for social interactions, where users can meet, chat, play, explore, and build virtual spaces [41]. Hence, Second Life is regarded as a communication platform within the context of construction training, facilitating individuals from diverse geographical locations to engage in concurrent online learning [19]. As Cowan and Kapralos [41] pointed out, Torque 3D, available under the MIT open-source license, is free and supports Windows and major web browsers. It uses TorqueScript scripting language, featuring a syntax similar to C++, to accomplish the majority of the game engine's functionalities. Table 3 summarizes the advantages and disadvantages of the XR development platform.

Table 3. Advantages and disadvantages of the XR development platform.

Development Platform	Advantages	Disadvantages	Application Example
Unity Engine	• Large and user-friendly community support • Wide range of supported platforms • Offers pre-built assets and plugins by the Asset Store • Supports Cross-platform development	• Slightly lower graphical fidelity compared to Unreal Engine • Primarily uses C#, unfriendly to developers preferring other languages	[18,44,49]
Unreal Engine	• High-quality graphics and realistic rendering • Powerful visual scripting with Blueprints • Robust community and support • Includes built-in VR development tools	• Features a steeper learning curve compared to some other engines • Some tasks may require C++, posing challenges for non-programmers	[16,50]
WebXR	• Allows creating VR experiences accessible via web browsers • Compatible with VR headsets supporting WebXR	• Limited to certain browsers and devices	[47]
Oculus First Contact Game	• Designed to be an introductory experience, accessible for beginners in VR development. • Provides access to Oculus-specific features • Optimized performance for Oculus devices	• Exclusive to Oculus hardware	[48]
Second Life	• Excels in creating vast, user-generated virtual worlds • Designed to be user-friendly for content creation in its virtual environment	• Not as robust as professional game engines in complex virtual world	[19,51]
Torque 3D Engine	• Open-source (MIT), allowing developers to modify and customize the engine • Supports multiple platforms for greater flexibility	• Smaller community compared to Unity and Unreal, potentially resulting in fewer resources and support	[52,53]

3.2.2. Display Device

The effectiveness of XR technology in construction training is influenced by the immersive level of display devices. The immersive level determines the depth of engagement and realism experienced by trainees within the virtual construction environments. Accordingly, XR display devices can be classified into three categories based on their immersive levels: non-immersive display (e.g., 2D display), semi-immersive display (e.g., Cave Automatic Virtual Environment (CAVE), Microsoft HoloLens), and immersive display (e.g., Head-Mounted Display (HMD)).

Two-dimensional display devices, such as desktop monitors [54] and mobile screens [52], represent the entry level of XR immersion. While these devices lack the depth and immersive qualities of more advanced options, they remain valuable for certain construction training scenarios. For example, mobile screens, found on smartphones and tablets, offer a portable and accessible XR experience. Gomes Jr et al. [55] used a tablet to detect the equipment from various user perspectives within the industrial scenario. This approach facilitates the real-time incorporation of actual information about these pieces of equipment through AR annotations.

CAVE systems represent a semi-immersive solution for construction training, providing a more engaging experience than 2D displays. CAVEs consist of immersive projection environments where virtual content is displayed on multiple surfaces, creating a room-sized virtual experience [56]. This immersive projection enhances spatial awareness and allows trainees to interact with the virtual construction site on a larger scale [17]. The use of motion tracking and gesture-based input devices further enhance the realism of the training experience [57]. One notable advantage of the CAVE systems, is their ability to facilitate collaborative learning [58]. Multiple trainees can simultaneously participate in the same virtual construction scenario, fostering teamwork and communication. This collaborative aspect makes CAVEs well suited for group training sessions and team-building exercises within the construction industry. In addition, because of the fundamental characteristics of AR technology, which entails superimposing computer-generated content onto the user's real surroundings, all AR-related display devices cannot offer a completely immersive experience. Consider Microsoft HoloLens as an example. While wearing HoloLens, users can maintain a clear view of their surroundings while concurrently observing holographic images seamlessly integrated into the real-world environment [59].

VR HMDs offer a fully immersive experience by seamlessly integrating virtual content into the trainee's field of view [60]. These head-worn devices, resembling visors, completely envelop the user's eyes and ears, creating a deeply immersive environment that isolates users from external stimuli. Offering a first-person perspective, VR HMDs transport trainees to a virtual construction environment, fostering a sense of physical presence [61]. Moreover, VR HMDs enable realistic simulations by tracking the user's head movements and adjusting the virtual environment accordingly [40,62]. This responsiveness contributes to the authenticity of construction training, enabling trainees to inspect virtual structures, interact with virtual objects, and practice construction tasks with an elevated sense of presence. Therefore, numerous studies chose headset devices for construction training, such as Oculus Rift [6], HTC Vive [63], Samsung Odyssey [64], Oculus Quest [65], and HP Reverb [21] et al.

3.2.3. Input Device

Input devices are the bridge between the physical actions of trainees and their interactions within virtual construction environments, including keyboard and mouse, touch screen, controller/joystick, tracking devices, and specialized input devices. Traditional input devices like keyboards and mouses remain relevant in XR construction training, especially in desktop-based training cases [66]. Touchscreen interfaces extend the reach of XR training to devices such as tablets and interactive displays [35]. Trainees can directly manipulate virtual elements by tapping, swiping, and pinching touch-sensitive screens. Moreover, controllers and joysticks are handheld devices that often include buttons, triggers, and other input mechanisms to facilitate various interactions within the virtual environment [40]. In construction training applications, motion controllers simulate the handling of tools and equipment, allowing trainees to practice tasks ranging from bricklaying to operating heavy machinery [6,8,15]. This can be particularly useful for hands-free interactions and can enhance the overall user experience. Tracking devices, such as sensors and cameras, play a critical role in capturing the real-world movements of trainees. These devices enable accurate positional tracking, allowing XR systems to replicate the trainee's movements within the virtual environment [8,14,65,67]. In construction training, tracking devices contribute to a high level of realism by ensuring that virtual interactions closely mirror the trainee's physical actions. Some specialized input devices are also adopted to enhance the training experience, such as operation panels [23], steering wheels [44], and foot pedals [18].

4. XR Application in Construction Training

From the review, XR applications in construction training can be categorized into five groups, including (1) safety training; (2) skill/knowledge acquisition; (3) equipment operation; (4) human–robot collaboration; (5) and ergonomics/postural training. Table 4 represents the distribution of these publications.

Table 4. The distribution of publications characterized by XR application in construction training.

XR Training Application	Representative Studies	NO. of Studies
Safety management	[8,14,17,19,20,24,44–50,52–54,57,64–66,68–91]	44
Skill/knowledge acquisition	[21,22,51,55,92–98]	11
Equipment operation	[6,15,18,23,35,99–103]	10
Human-robot collaboration	[7,63,104–108]	7
Ergonomics/postural training	[16,67]	2
Total		74

4.1. Safety Management

In the realm of construction training, the predominant current research focuses on safety management. Over the past 15 years, 44 papers have been published, constituting 59.5% of the total selected papers. Construction sites pose various risks, such as fall hazards, electrical hazards, objects striking, and hazards related to collapse or caught-in/between situations [24,45]. Ensuring the safety of workers is paramount to the construction industry, and XR technology presents an innovative approach to training that surpasses the traditional methods. Researchers achieve this by devising construction tasks or scenarios that incorporate one or more hazards, allowing safety managers or workers to enhance hazard perception awareness, reduce accidents, or gain sufficient knowledge to respond effectively to hazardous situations [49,68].

XR technology facilitates the development of highly realistic safety simulations, enabling trainees to encounter hazardous scenarios within a controlled virtual environment. Moreover, Trainees can use XR devices to inspect the environment, identify hazards, and make informed decisions on how to address or avoid them. In a study conducted by Rey-Becerra et al. [20], VR was employed to replicate an overhead work scenario on a construction site. Participants, equipped with VR headsets (Pico Neo 3 Pro) and controllers, engaged in three virtual tasks: painting a façade using scaffolding, transporting two boxes on a platform, and installing a camera at the roof's corner. Throughout the simulation, participants were tasked with selecting the appropriate personal protective equipment and reporting unsafe situations and hazards using a virtual tablet. Another approach, proposed by Wolf et al. [14] involved an AV method to assess trainees' hazard awareness in a virtual work environment. AV technology allows for the tracking of the user's hand motion and details of all entities in the virtual world, enabling the user to interact with a virtual angle grinder (with real weight, shape, and function) using their hand. The virtual scenario tasked participants with operating the angle grinder to cut a pipe while ensuring compliance with the prerequisites for themselves and their virtual animated coworkers represented in the simulation.

XR technology also enables dynamic and lifelike emergency response exercises, giving trainees practical experience in responding to critical situations. Wang et al. [46] used BIM and Unity3D to develop a virtual fire training system aimed at enhancing safety evacuation awareness. In addition, following simulated scenarios, XR facilitates in-depth post-incident analysis. Trainees have the opportunity to review their actions, comprehend the repercussions of their decisions, and explore alternative courses of action [87].

4.2. Skill/Knowledge Acquisition

One purpose of construction training utilizing XR technology is to enhance the competencies and expertise of construction workers. In this review, 11 papers, accounting for 14.9% of the total, were dedicated to applications related to skill and knowledge acquisition—the second-largest focus area in construction training.

In construction training, VR can provide trainees with a three-dimensional virtual space, replicating diverse construction sites with different layouts, structures, and spatial challenges. Through VR devices, trainees can interact with and manipulate virtual objects, promoting a deeper understanding of spatial relationships. Conesa et al. [21] developed an immersive shared virtual scenario enabling multiple students to collaborate in building a model. This study's results demonstrated that VR has the potential to enhance the spatial skills of trainees.

The primary objective of AR training is to augment the skills and knowledge of construction professionals. Notably, in construction assembly tasks, AR proves valuable by offering workers graphical models enriched with contextualized information. This assistance enables them to carry out assembly work more quickly and accurately [109,110]. For instance, Gabajova et al. [96] introduced a virtual training task where trainees were tasked with assembling an industrial plug. Using AR technology through a tablet, the group could access each step of the assembly procedure, resulting in a reduction in the average assembly time compared to providing only a user manual. Similarly, Hou et al. [22] employed AR to embed digitized information into a real-world workspace displayed on a TV monitor. This approach furnished workers with the correct assembly procedure, leading to an enhanced accuracy in completing the pipe assembly by the trainees. AR proves to be a valuable tool in assisting and allowing trainees to practice and refine their assembly skills.

Other construction skills and knowledge can also be gained through XR technology. For example, Goulding et al. [97] employed VR interactive training, enabling trainees to experiment with offsite production work practices within a secure and controlled environment. This approach allows trainees to explore and grasp new methods, processes, and modes of thinking. Furthermore, Osti et al. [98] developed a virtual sector focused on timber-based construction, offering effective training for workers and enhancing the manual skills of young carpenters.

4.3. Equipment Operation

XR technology has also been implemented in construction equipment training, with a total of 10 studies (13.5%) reviewing its use. Primarily within VR environments, XR replicates the controls and functionalities of authentic construction machinery. This innovation allows trainees to engage in hands-on practice with equipment like excavators, forklifts, and cranes within a secure environment, eliminating the potential dangers associated with using actual machinery [18]. Virtual training not only provides a risk-free setting but also yields cost savings by mitigating expenses such as fuel consumption and equipment rental [30]. XR simulations enable trainees to acquaint themselves with equipment interfaces, hone precise maneuvers, and cultivate the skills essential for secure and efficient equipment operation. The training modules further allow for a progressive learning approach, enabling trainees to advance through various difficulty levels. This structured progression ensures that trainees master basic controls before tackling more intricate tasks, facilitating a systematic and effective skill development process.

Liu et al. [18] introduced a multi-user excavator teleoperating system that uses two joysticks and two pedals to simulate a real excavation experience. This system can facilitate collaborative work between an excavator operator and a signaler. Pooladvand et al. [100] created a crane simulation system within a virtual reality environment. This system automatically produced lifting objects and obstacles, incorporating comprehensive lift studies and a crane path planning system for real-time evaluation. It assessed the safety and feasibility of comprehensive lift planning in real time, providing crane operators and lift engineers with experience comparable to actual operation. Other small equipment like drones [101] and angle grinders [99] can also be trained using VR. These studies demonstrated the promising potential of XR for diverse equipment operating training.

4.4. Human–Robot Collaboration

As robotics become increasingly integrated into construction processes, XR facilitates training scenarios involving human–robot collaboration. Recent research has successfully merged VR with robotic systems, creating a seamless environment for data sharing and interaction [63]. In a study by Ye et al. [104], a comprehensive robot-assisted motor training system was introduced to enhance expert motor skills through a keyhole welding training task. The system recorded the movement process of expert motor skills using haptic feedback from the robotic system. The recorded data were then played back to the trainee through perceptual learning, enabling them to comprehend the movement pattern through proprioception. The system offered features such as repetition, pausing, and adjusting training speed, thereby aiding novices in mastering motor skills. Another instance of human–robot collaboration is highlighted in a study by Adami et al. [7]. The researchers investigated whether participation in virtual training with 25 trainees remote operating a demolition robot could enhance trust in the robot, self-efficacy, mental load, and situational awareness. The results demonstrated that VR training significantly improved cognitive factors compared to traditional face-to-face training. Consequently, the utilization of VR technology for training human–robot collaboration holds immense potential for the future.

4.5. Ergonomics/Postural Training

XR implementations in ergonomics/postural training are comparably limited, comprising only two journal articles. Nonetheless, in the construction industry, maintaining proper ergonomics and posture is critical to preventing musculoskeletal injuries, reducing the risk of injury, and improving overall health [111]. XR technology proves valuable in simulating the postures adopted by construction workers during their daily tasks. It not only evaluates these postures but also fosters proper ergonomic awareness and posture, thereby mitigating the risk of injuries associated with repetitive tasks or awkward postures. For example, Akanmu et al. [67] developed a cyber-physical postural training system that leverages VR technology to integrate virtual environments with physical architectural resources, such as wood. In this system, trainees utilized wearable sensors (IMUs) and a Vive tracker to ascertain their position and posture within the virtual environment. As trainees engaged in wood frame construction, the system captured data on body part rotations for analysis. Subsequently, it delivered instructional material aimed at promoting safe posture, thus enhancing the overall effectiveness of postural training. Although XR has minimal application in construction training, this technology provides a platform to create a safer and healthier working environment in the construction industry.

5. Participants of XR Training Experiments

XR training experiments encompass a diverse range of participants, primarily classified into two categories: students and construction professionals. Students typically come from disciplines associated with construction, such as construction engineering, civil engineering, mechanical engineering, and electrical engineering. On the other hand, construction professionals encompass various roles, including welders, concrete workers, rebar workers, carpenter workers, electric construction site workers, operators, safety managers, project managers, site managers, and safety inspectors. In Figure 7, among the 74 publications obtained for this review, 23 articles exclusively featured students, representing 31% of the total, while an equivalent number of articles concentrated on the involvement of construction professionals. Furthermore, 18 articles (24%) showcased a mixture pattern, with participants including both student and construction professional roles. Notably, the identity of the participants remained unspecified in 10 articles, constituting 14%.

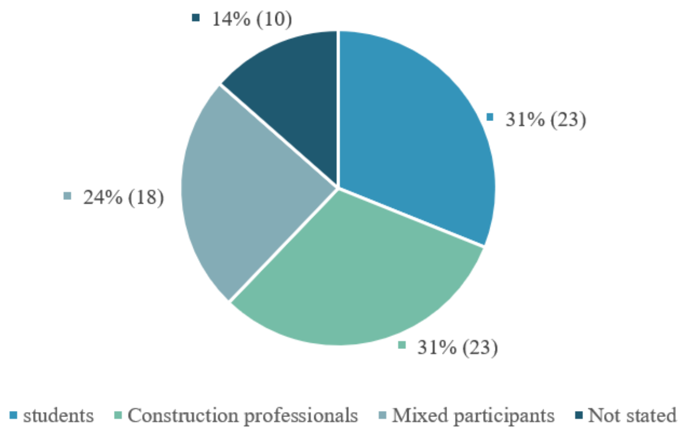

Figure 7. Percentage of participants involved in the experiments.

Numerous studies have observed variations in training outcomes for trainees who are either students or working professionals. For example, Eiris et al. [54] conducted an experiment involving 38 construction students and 38 construction professionals, comparing a 360 degree panorama with a virtual reality safety training platform featuring four hazards. The results revealed that students perceived the 360 degree panorama as more realistic than the virtual reality environment, whereas construction professionals did not discern a significant difference. In addition, Adami et al. [63] undertook a study with 25 construction workers and 25 graduated construction engineering students, focusing on demolition robot operation training. The findings indicated that students exhibited greater knowledge acquisition, while workers demonstrated higher levels of trust and self-efficacy in the robot. Consequently, the effectiveness of XR training appears to be role-specific within the construction domain, suggesting the need for customized training content and methodologies tailored to distinct roles.

The outcome of XR training is also influenced by the trainee's experience. For instance, in a safety training study by Yu et al. [74], 40 novice and 40 experienced workers underwent virtual construction site training involving 17 hazardous scenarios. The results indicated that novices exhibited significantly higher safety learning gains compared to their experienced counterparts. Such comparisons between novice and experienced workers offer valuable insights into the adaptability of XR training for individuals at various stages of their careers.

Some researchers have focused on the linguistic background of the trainees who participated in the XR training experiment. Afzal and Shafiq [50], for instance, employed BIM-based VR technology to conduct safety training focused on fall hazards in a multilingual setting in the United Arab Emirates. To mitigate the impact of language differences, participants in the training opted for a construction hierarchy, enabling them to discuss, address, and explain primary risks to on-site workers who did not share a common language. Understanding how participants communicate in virtual environments is crucial for designing XR training experiences that facilitate clear and effective interactions.

The diverse demographic composition of experiment participants engaged in XR training introduces a multifaceted dimension to the evaluation of its effectiveness. The characteristics of the study sample selected for XR training play a vital role in influencing the ultimate training effect and impacting the overall validity of the study's findings. To ensure the broader applicability of XR training outcomes, researchers should carefully consider participants' features throughout the evaluation process. In addition to the trainee's identity, work experience, and language background, other factors merit consideration, such as the gender and age of the trainees, their previous experience with XR training, etc. Additionally, it is important to consider the sample size, as a sample that is too small may fail to adequately represent a diverse group of individuals. Considering the characteristics of XR experimental participants can enhance the depth of analysis, providing a more nuanced understanding of factors influencing XR training.

6. Challenges of XR Training

This paper presents a comprehensive review of 74 articles on XR training in construction published between 2009 and 2023. Although the application of XR technology in the field of construction training is becoming more and more widespread and shows the advantages and great research potential of this technology, it is undeniable that it is still in the early stage of XR technology development. Therefore, analyzing the main obstacles and challenges that exist in current XR training technology can help researchers understand the issues that they may face when conducting research on XR technology in the construction training domain.

As shown in Table 5, this paper describes the challenges faced by VR, AR, and AV technologies in the application of construction engineering training. VR consists of nine main aspects:

- Visual interface design: The current equipment constrains the trainee's visual perspective, and overcoming this limitation to attain a more extensive and panoramic view poses a challenge.
- Motion capture technique: Current motion capture technologies come with calibration challenges, and the precision of captured positions is not sufficient.
- Content development: Creating high quality and relevant VR training content specific to the construction industry can be time consuming and resource intensive. Developing realistic simulations, 3D models, and interactive scenarios that accurately represent construction processes and hazards requires expertise and collaboration between subject matter experts, instructional designers, and VR developers.
- Multi-sensory: The current sensory feedback primarily involves visual and auditory stimuli; incorporating additional sensory feedback can enhance the alignment of the virtual world with the real world.
- Health and safety: Ensuring the safety of trainees during VR simulations is crucial. Designing VR training experiences that accurately replicate real-world construction hazards and safety protocols while maintaining a safe training environment can be challenging. It is essential to strike a balance between realistic training scenarios and minimizing the risk of physical or psychological harm to trainees.
- Assessment method: Most VR training assessments rely on questionnaires to gauge effectiveness, yet this evaluation method depends on the subjective sentiments of the trainees.
- Scalability and accessibility: Ensuring accessibility for workers with diverse backgrounds, abilities, and language proficiency can be a challenge that requires careful consideration during VR training development.
- Long-term effect: Most VR training evaluates short-term effectiveness, whereas the ultimate goal of training is for trainees to acquire a skill or knowledge over the long term.
- Skill requirement: Mastering VR technology demands highly specialized skills and can prove challenging for many individuals.

Challenges of AR technology application in the field of construction include two aspects: (1) Health and safety: AR training should prioritize safety by accurately representing construction hazards and safety protocols. Prolonged use of head-mounted displays can cause visual discomfort for trainees. (2) Tracking technique: It is challenging to track motion in unprepared environments. Regarding challenges in AV technology, creating a high-fidelity environment with multiple participants and well-designed training assistant content proves to be difficult.

Table 5. Challenges of XR training application in the construction industry.

XR Technology	XR Training Application Challenges	Description	References
VR	Visual interface design	The design of the visual interface may prioritize situational comprehensiveness over realism in recent studies	[18]
		Trainees' view is limited, and they cannot accurately understand their situation.	[23]
	Motion capture technique	Motion capture technique requires cumbersome calibration before each new task trial.	[18]
		Moton tracking is not accurate enough.	[83]
	Content development	Training contents inconsistent with real-time life cause confusion among participants.	[99]
		Factors like wind, weather, temperature, lighting, and visibility, are not adopted.	[100,101]
		The problem remains of how to measure the task complexity and its impact.	[15]
	Multi-sensory	Improve the training experience by adding haptic, locomotion, and auditory feedback, etc.	[24,106]
	Health and safety	VR-based training may have physical side effects	[8,24,48,107]
		Tasks requiring dexterity, involving high force, sudden changes in force, large accelerations, or rapid movements carry a risk of injury.	[104]
	Assessment method	The measurement of the questionnaire is subjective.	[20,44,80]
		Negative emotions are not measured during training.	[45]
	Scalability and accessibility	Ensuring training accessibility for workers with diverse backgrounds, abilities, and language proficiency can be a challenge	[20,72]
	Long-term effect	Lack of research on the long-term effect of training results	[45,53,70,74,81,87,106]
	Skill requirement	The development process requires special skills and extra effort.	[19,99]
AR	Health and safety	Prolonged use of head-mounted displays can cause visual discomfort for trainees	[55]
	Tracking technique	Markerless tracking and 3D feature-based tracking are not yet fully developed for application, particularly on mobile devices.	[22]
AV	Content development	Lack of multi-user virtual environment with varying degrees of assistance in achieving training objectives	[14]

7. Conclusions

The purpose of this literature review was to provide a comprehensive overview of research on extended reality (XR) technology training in the construction industry. This study was conducted by systematically searching the relevant literature over a period of 15 years, from 2009 to 2023, resulting in 74 journal articles. This literature review first describes the selected publications as a whole and then shows the technology of XR including its development platform, display device, and input device. Regarding the application of XR training in the construction industry, it can be categorized into the following five categories: (1) safety management (2) skill/knowledge acquisition (3) equipment operation (4) human–robot collaboration (5) ergonomics/postural training. In addition, this study also investigated the challenges faced in the implementation of XR in construction training applications. The specific challenges encountered in VR, AR, and AV training applications were presented separately.

This study contributes to three main areas. Firstly, it provides an overview of the current state of XR technology (VR/AR/AV) and its applications in construction training, offering insights into the latest developments. Secondly, this review also delves into the identity characteristics of XR trainees, marking the first such analysis in the literature and exploring their potential impact on XR training experimental results. Lastly, through a comprehensive analysis of the existing literature, this study identifies challenges encountered in XR training within the construction industry. This information provides audiences with insights into the current obstacles in XR training development and hopes to offer guidance for future advancements in this field.

It is essential to acknowledge its limitations. First, the focus on XR technologies exclusively within the realm of construction training may inadvertently neglect broader applications within the construction industry. Additionally, the sourcing of 74 journal articles solely from the Scopus database may have resulted in the omission of pertinent literature from other databases, potentially limiting the comprehensiveness of the findings. Moreover, while the three facts of XR technology are introduced, it is imperative to recognize that this may not capture the entirety of the expansive XR landscape. While recognizing certain limitations, it is expected that the findings presented in this review serve as a valuable reference for fellow researchers in their respective fields.

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