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Review article

A state-of-the-art analysis of virtual reality applications in construction health and safety

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ABSTRACT

The construction industry contends with high injury rates, emphasizing the need for innovative preventive measures in construction health and safety (CHS). While previous studies have investigated the potential applications of virtual reality (VR) in the construction industry for different purposes, an in-depth study on VR in the CHS context is lacking. Hence, this study provides a state-of-the-art analysis of VR applications in CHS, employing a dual scientometric and systematic review approach. A scientometric analysis is conducted to examine annual publication trends, keyword co-occurrences, and science mapping of publication outlets, alongside mapping the contributions of leading countries in this domain. This analysis reveals a marked increase in research interest and identifies central thematic connections within the body of literature. The systematic review assesses VR technologies, including immersive, desktop-based, BIM-based, 3D game-based, and augmented reality, addressing their roles in hazard identification and safety training. The study also underscores challenges like infrastructure, content modeling, and interoperability and proposes directions for future research. Recommendations include probing into VR's role in cognitive safety risks and the impact of users' prior safety knowledge on learning outcomes. This study suggests that developing tailored VR experiences for specific user groups could significantly advance safety practices in the construction industry.

1. Introduction

Construction industry injury rates are higher than those in many other job sectors, resulting in deaths and substantial financial loss [1–4]. Such occurrences have generated discussion on safety over time. Studies have shown that most accidents associated with construction projects were caused by the absence of proactive and preventive measures like identifying and controlling possible sources of risk, educating the workers on safety awareness, and alerting the safety authorities on related safety issues [5]. Accordingly, numerous hazards on construction sites remain unrecognized or inadequately managed, leading to injuries. Previous studies indicated that almost half of hazards on construction sites remain unrecognized [6–9]. Workers are often exposed to unforeseen safety risks since innovative preventive measures are not taken against such unknown hazards.

VR is a technology that can help foresee possible hazards on site. However, its lack of adoption can make it challenging to detect construction safety hazards [10,11]. Despite the construction sector's embracing digital technologies for cloud-based workflows, from the commencement of a project through design, execution, and closure, the industry lags in adapting these technologies to enhance construction health and safety (CHS) [12]. According to Pereira et al. [13], there are various inadequacies that traditional safety training modules have, most of which render them ineffective. The conventional means of ensuring

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safety are based on the expertise or assumption of the safety managers that hazards are present or absent [14,15]. The traditional methods utilized to address CHS challenges have a limited impact on mitigating hazards. Still, VR can enhance employees' capacity to recognize potential risks, strategize for safety measures, and effectively handle safety protocols. This, in turn, decreases the chances of errors leading to construction disasters [12,16].

VR is a technology that utilizes an entirely computer-generated environment, allowing the human to be transformed from the perception of reality into a virtual environment using peripheral equipment such as headsets, glasses, and multiple displays [17]. The leading VR applications are prevalent in the gaming and entertainment sectors, although sports, education, marketing, and tourism have also explored its potential [18]. VR training is a growing trend among firms across diverse sectors for improving productivity. For instance, UPS [19], a company that delivers parcels, uses VR to train its drivers. It has also been used for marketing by architectural firms, scheduling and coordination by construction firms, and other applications [20]. VR techniques are specifically utilized to transfer knowledge to workers, determine hazards on site, and prevent them from occurring [21].

Several scholars have reviewed the utility of digital visualization techniques in the construction safety field, with several review articles published. Due to VR's strength, its research is augmenting the construction safety domain. For instance, Bhoir and Esmaeili [22] study focused on the utilization of VR environments in enhancing construction safety; Guo et al. [23] studied visualization technologies to manage construction safety. Kassem et al. (2017) explored the application of virtual environments for safety training within the construction and engineering domain. Li et al. [24] reviewed VR and AR systems for Construction safety. Wang et al. [25] analyzed VR applications in training and education within the construction engineering discipline. Mihić et al. [26] examined previous uses of advanced innovative information technologies in C.H.S. Moore and Gheisari [21] worked on VR and MR for Construction Safety. Zhang et al. [27] looked at monitoring occupational health and safety of construction site workers using vision-based technology. Akinlolu et al. [28] examined construction safety management technologies. Afzal et al. [12] explored virtual-design construction technologies for construction safety. Cruz and DAJAC [29] reviewed VR applications in construction safety.

Table 1 highlights existing reviews relating to VR and related technologies applications in construction safety. The table includes the research method, timespan, and findings of the previous studies. While existing studies have contributed to the domain, the literature lacks a comprehensive and critical analysis of previous studies in the last decade. Additionally, there is lack of a synthesis of extant literature using a combination of scientometric and systematic analysis. Hence, this study is conducted to fill these gaps with the following objectives:

- To identify relevant literature in VR-CHS domain and conduct scientometric analysis of these studies.
- To systematically review VR applications in CHS and discuss their associated challenges.
- To identify gaps in the extant literature and provide recommendations to fill them.

2. Research methodology

This study adopts a mixed-methods approach, integrating qualitative and quantitative elements, to comprehensively review VR in CHS. The quantitative component encompasses a systematic literature search and a scientometric analysis of the identified studies. In parallel, the qualitative aspect involves a systematic review of the retrieved literature. This process aims to identify and synthesize key themes and ensures a thorough and unbiased understanding of the state-of-the-art in VR-CHS. The methodology for literature retrieval is illustrated in Fig. 1, while the framework of the study is depicted in Fig. 2. The subsequent sections

Table 1
Overview of the methods and the research focus of the previous review articles.

Authors	Research Method	Timespan	Research Findings
Zhou et al. [30]	Systematic review	1986–2012	The results outlined technology applications for construction safety. Since 1986, the number of studies addressing this topic has increased.
Bhoir and Esmaeili [22]	Literature Review	2001–2014	Based on the results of the interviews, organizations most commonly provide safety training through instructor-led manuals, audio/visuals, and hands-on exercises.
Zhao and Lucas (2015)[31]	Literature Review	NA	The authors concluded that VR simulations had been proven to improve safety training within the construction sector.
Guo et al. [23]	Critical review	1999–2015	The study shows that visualization technologies can enhance safety management by assisting in safety education and training, identifying work hazards, and monitoring and warnings on-site, but it also has limitations.
Kassem et al. (2017) [32]	Systematic review	2006–2015	According to the findings, there is a need for more studies on the VE's effectiveness as a safety learning intervention throughout the risk management process.
Awolusi et al. (2018) [33]	Literature review	NA	The review indicates that construction safety performance metrics can be monitored and measured using wearable technologies implemented in other industries.
Li et al. [24]	Content analysis-based review	2000–2017	Immersive VR/AR applications are increasingly used in the workplace to visualize complex situations, build risk prevention knowledge, and undergo training.
Getuli et al. (2018) [34]	Literature review	NA	VR and BIM appear to be dedicated to adding to the headway of advancing the recent safety management practices.
Wang et al. [25]	Critical review	1997–2017	The evolution of VR technologies utilized in construction engineering training and education has developed over time. It transitioned from desktop-based VR, immersive virtual reality (IVR), and 3D game-based VR to BIM-empowered VRS.
Awolusi et al. (2019) [35]	Literature review	NA	The adoption of Wearable Sensing Devices and the Internet of Things is anticipated to encourage proactive and dynamic construction safety management methodologies to reduce construction sites' fatalities and injuries.
Moore and Gheisari [21]	Systematic review	2007–2018	Most researchers utilized PC screens and consoles for system interaction, picking this minimal expense regularly accessible fringe equipment over more immersive choices like CAVEs and HMDs.

(continued on next page)

Table 1 (*continued*)

Authors	Research Method	Timespan	Research Findings
Grassini & Laumann (2020) [36]	Literature review	2014–2019	The study revealed that implementing VR as a seamless component of the work underlying the safety instruction is an assumption that such technology might benefit operators and follow safety protocols or stay away from potentially dangerous situations that may arise at work
Shafiq et al. (2021) [37]	Critical analysis	2010–2019	The study indicated that Virtual design construction technologies can substantially enhance construction safety.

elaborate on this methodology in detail, providing insights into the search protocols, analysis techniques, and thematic synthesis.

2.1. Retrieval of relevant studies

Fig. 1 delineates the systematic methodology employed for retrieving pertinent studies in this research, characterized by its rigor and potential for replication. The search commenced with an initial query using specific keywords within the Scopus database, chosen for its comprehensive coverage and strict indexing protocols (Taiwo, Ben Seghier et al., 2023; [38,39]). The TITLE-ABS-KEY field was used for this search term: "VR" OR "Virtual Reality" OR "Immersive Technologies" OR "Vision-based" OR "Visualization Technology" OR "Wearable Technology" OR "Virtual Design AND "Construction Technologies" OR "Construction Health" OR "Construction Safety" "Construction Health Safety." This search string returned 261 articles. Subsequently, inclusion criteria, including 1) peer-reviewed articles published in journals or conference proceedings, 2) articles focusing on VR applications in CHS, 3) articles published between 2010 and 2023, and 4) articles written in the English language were defined. This resulted in 220 articles being retained for further evaluation. The next phase involved a detailed screening of articles for eligibility. During this stage, each article's title and abstract were scrutinized, leading to the exclusion of 31 articles. The remaining 189 articles underwent full-text screening to assess their suitability based on predefined relevance and quality criteria. This intensive screening resulted in the removal of an additional 112 articles. Furthermore, the snowballing technique was applied to the 77 articles that passed the full-text screening. Snowballing is a method which involves examining the reference lists of the selected papers to find more pertinent research that were missed in the first search. This process also included forward and backward searching, whereby the citations of the articles were checked, as well as later studies that cited them [40,41,42]. Through this iterative process, 29 new articles were identified. The final count of selected articles that met all the criteria and were chosen for inclusion in the research amounted to 106. These articles form the corpus of literature from which insights and discussions are drawn for the scientometric and systematic review.

2.2. Scientometric analysis

Scientometric analysis is a quantitative technique employed to assess the development, structure, and interrelation of scientific disciplines through the evaluation of published literature [43,44]. It serves as a pivotal tool in understanding the evolution of academic fields, identifying core topics, influential studies, and emerging trends. Various software tools are available for conducting scientometric analyses. These tools differ in their analytical capabilities, graphical representations, and data processing strengths [45,46]. Among the plethora of options, VoSviewer and Gephi stand out for specific functionalities that align with the scope of this study. The rationale for selecting VoSviewer and Gephi in this study is twofold. Firstly, VoSviewer's strength in revealing patterns and clusters within keyword co-occurrences provides a clear visualization of the thematic concentration and dispersion in the literature. Secondly, Gephi's advanced graphing capabilities allow for detailed science mapping, revealing the interaction between articles in a field, which is crucial for identifying global research networks and collaborations. The scientometric analysis in this study focuses on four specific dimensions: annual publication trend, keywords co-occurrence, and science mapping of publication outlets and countries.

2.3. Systematic analysis

The systematic analysis represents an examination of the scholarly works pertaining to VR in C.H.S. From the initial set of 106 articles, a further evaluation was conducted focusing on the novelty of the research and the thoroughness with which VR methodologies were employed within the previous studies. This stringent assessment narrowed the pool to 64 articles that exhibited significant innovation and methodological rigor.

In the subsequent phase of analysis, the selected 64 papers underwent a thorough content examination. The framework for this examination was structured around a coding system designed to align with the previously outlined research aims. The sub-coding method, as described by Saldaña (2015), was employed due to its efficacy in managing and dissecting a wide array of data, which has been demonstrated in prior research, including the work by Braekers et al. (2016). This methodological choice is particularly suited for the granular analysis required for the content, as it allows for the initial coding categories to be refined and organized into more detailed classifications and hierarchical structures, as noted by Saldaña (2015). The content analysis was structured to segment the literature into five distinct domains: (1) an overview of VR systems, (2) the integration of VR within CHS, (3) the technological and methodological attributes of VR-CHS studies, (4) VR-CHS application domains, and (5) the challenges linked to VR implementations in the field. Furthermore, the analysis was instrumental in pinpointing existing literature gaps. Based on these findings, strategic recommendations were formulated to address these gaps, thereby contributing to the advancement of knowledge in the VR-CHS domain.

3. Result of the scientometric analysis

3.1. Annual publication trend

Fig. 3 presents the annual publication trend for research articles within the field of VR-CHS from the year 2010 through 2023. The bar graph delineates the number of publications per year, visually representing the scholarly output over the examined period. The data indicates a nascent stage in the early years, with only a single publication recorded annually from 2010 to 2014. This trend exhibited a modest increase in the subsequent years, with two publications annually from 2015 to 2017. A noticeable uptick in productivity is apparent beginning in 2018, with eight publications, suggesting a promising interest in the field.

The progression continues with a steady climb, reaching 17 publications in 2020. A slight decline to nine publications in 2021 is observable, potentially attributable to global circumstances impacting research activities. However, a subsequent rebound and growth phase is evident, with the number of publications rising to 20 in 2022 and peaking at 26 in 2023. This upward trajectory underscores a growing recognition of the importance of VR technology in enhancing CHS protocols. The general trend reflects an increasing academic and industry focus on leveraging VR as a tool for safety training, risk assessment, and process visualization in the construction sector. The peak in 2023 signifies a maturation of the field and an established recognition of

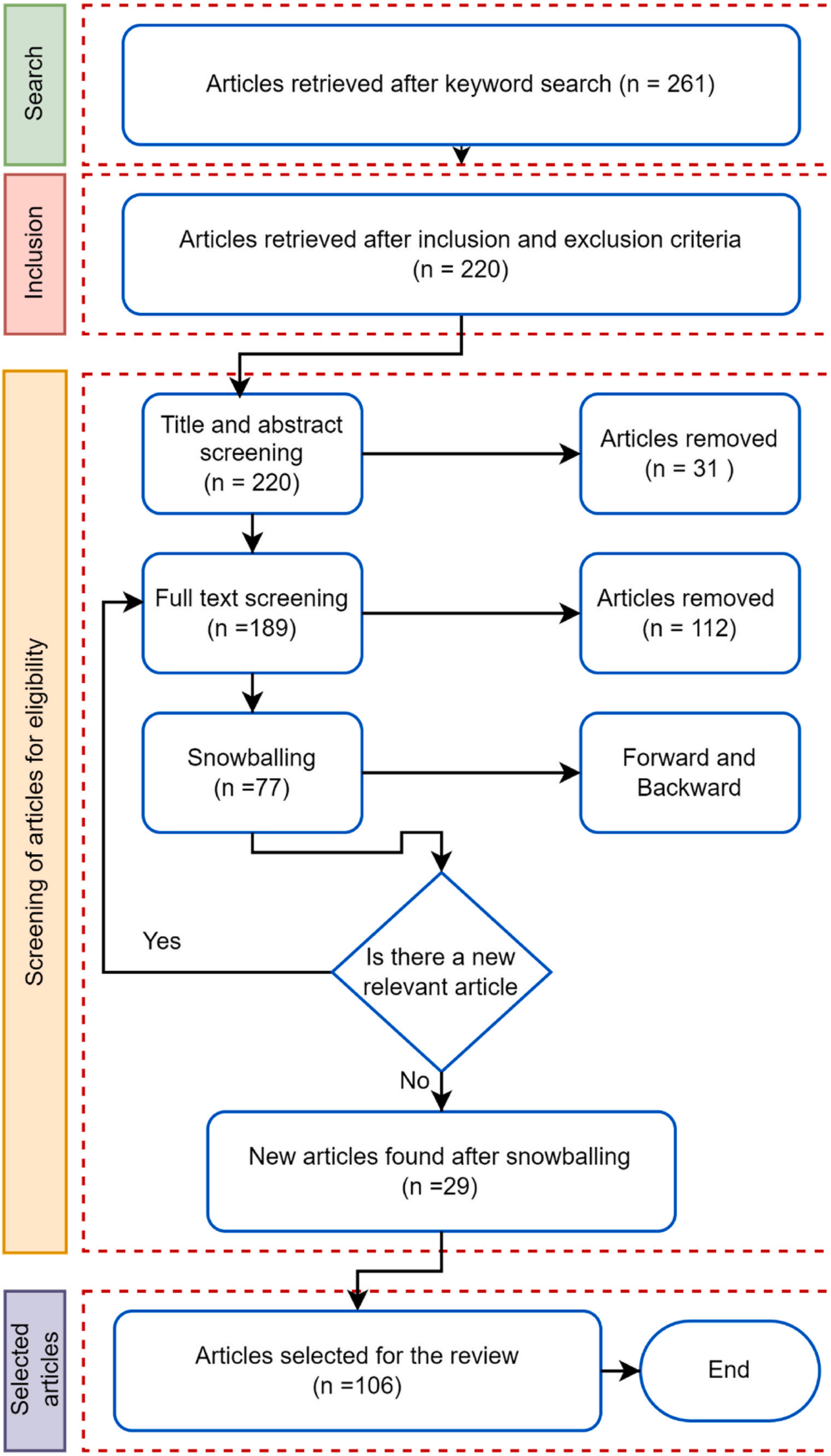

Fig. 1. Literature retrieval procedures.

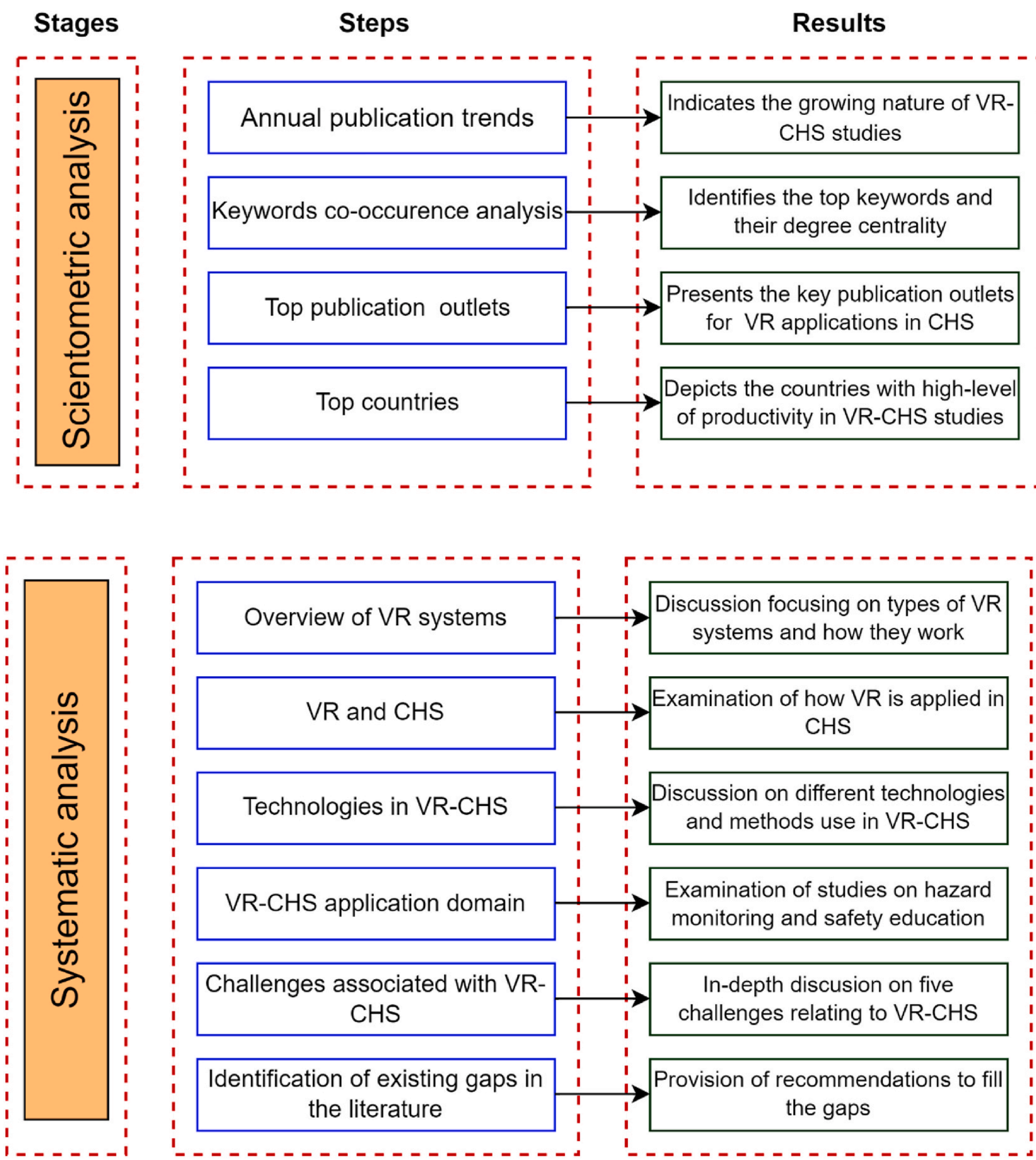

Fig. 2. The framework of the study.

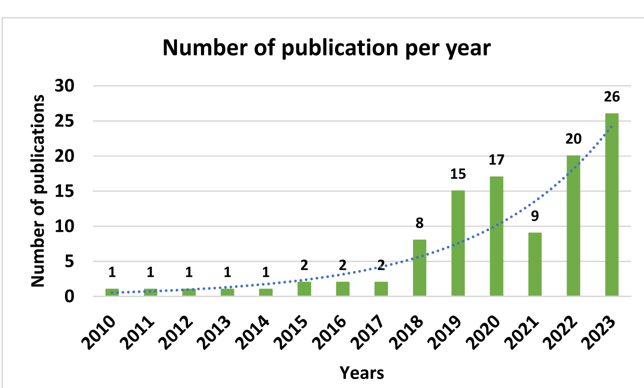

Fig. 3. Annual publication trend.

the value that VR-CHS studies contribute to advancing construction safety practices.

3.2. Keyword co-occurrence

The analysis of keyword co-occurrence is instrumental in scientometric research, as it elucidates a scientific field's thematic structure and conceptual underpinnings. The examination of the frequency and patterns of keywords appearing together within a body of literature can aid researchers in identifying the most salient topics and discerning the interrelatedness of concepts within the domain [40].

In this study, VOSviewer was utilized to conduct a co-occurrence analysis of keywords drawn from the 106 articles. The parameters were configured such that only keywords appearing a minimum of three times were included in the analysis. Out of a total of 951 keywords identified, 112 met this criterion. To enhance the accuracy of the analysis, the thesaurus file option in VOSviewer was employed to consolidate keywords with synonymous meanings but varied spellings or representations. For instance, "immersive virtual reality" and its abbreviation "ivr" were amalgamated under the unified term "immersive virtual reality," thereby streamlining the dataset and refining the

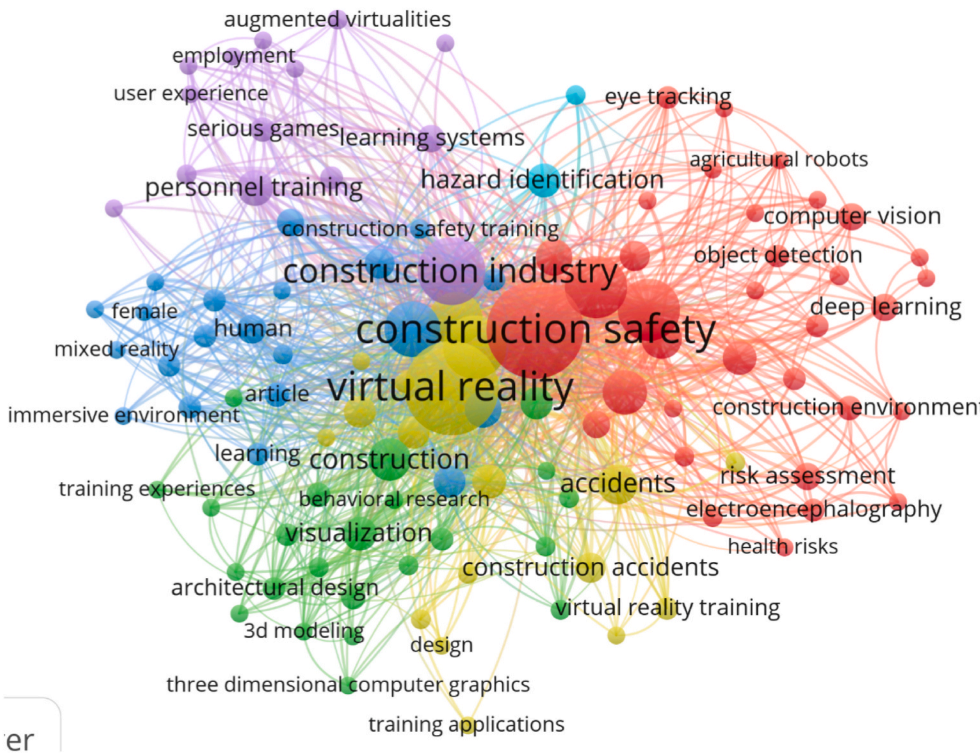

Fig. 4. Science mapping of keyword co-occurrence network.

analysis.

Fig. 4 presents the resultant science mapping of the keyword co-occurrence network. The visualization is composed of six distinct clusters, each denoted by a unique color and representing a thematic grouping of interconnected keywords. The size of the nodes reflects the frequency of the keywords' occurrence, while the thickness of the connecting lines indicates the strength of the co-occurrence relationships. The network mapping reveals "virtual reality" and "construction safety" as prominent central nodes, indicative of their principal relevance in the field. Surrounding these are clusters highlighting interrelated themes such as "hazard identification," "risk assessment," "VR training," and "immersive environments," among others. This visual representation provides a strategic overview of the field's focus areas, offering insights into current research emphases and potential avenues for future inquiry.

Table 2, generated through Gephi's analytical capabilities, provides a ranking of keywords based on their degree centrality within the VR-CHS research domain. According to this table, the top five keywords, namely "construction safety," "virtual reality," "e-learning," "construction industry," and "occupational risks," exhibit the highest degree centrality scores. This suggests that these terms are not only prevalent within the literature but also serve as nexus points, interlinking diverse discussions and themes. For instance, the keyword "e-learning" intersects with "virtual reality" by representing the shift towards digital platforms for education and training within the "construction industry." It reflects a trend toward adopting virtual environments for the purpose of enhancing learning outcomes, particularly in safety training and competency development [7].

Table 2
Top 20 Keywords in VR-CHS research domain.

Keywords	Total Link Strength (TLS)	Occurrence	Degree Centrality	Betweenness Centrality
Construction Safety	727	88	111	344.6221233
Virtual Reality	687	83	106	187.0855404
E-Learning	362	38	99	463.2402902
Construction Industry	396	43	99	188.8091182
Occupational Risks	338	37	89	422.6198047
Hazards	337	37	86	375.7465567
Accident Prevention	273	29	82	0.8985689
Safety Training	232	27	74	314.9635547
Construction Workers	170	19	68	109.9690658
Construction	153	17	62	61.43363237
Construction Sites	142	16	62	58.29265293
Safety	127	13	58	68.67786812
Robotics	121	13	56	95.15598036
Personnel Training	139	12	54	88.40934816
Safety Engineering	95	10	54	59.19518848
Accidents	133	15	53	12.16432179
Hazard Recognition	93	9	52	72.28227439
Immersive Virtual Reality	99	10	51	76.1847236
Training	119	10	51	27.18714219
Visualization	106	11	48	5.27933635

3.3. Publication outlets

The analysis of publication outlets highlights the dissemination channels through which research findings are communicated within the academic community. Identifying the most influential journals and conferences is crucial for understanding the landscape of scholarly communication and recognizing the primary platforms for knowledge exchange [43]. In this study, VOSviewer was utilized to establish a threshold for the selection of the most relevant publication outlets in the VR-CHS domain. The criteria were set to include only sources with a minimum of two documents and two citations. Out of 56 sources identified, 16 met these criteria. Gephi was then employed to create a

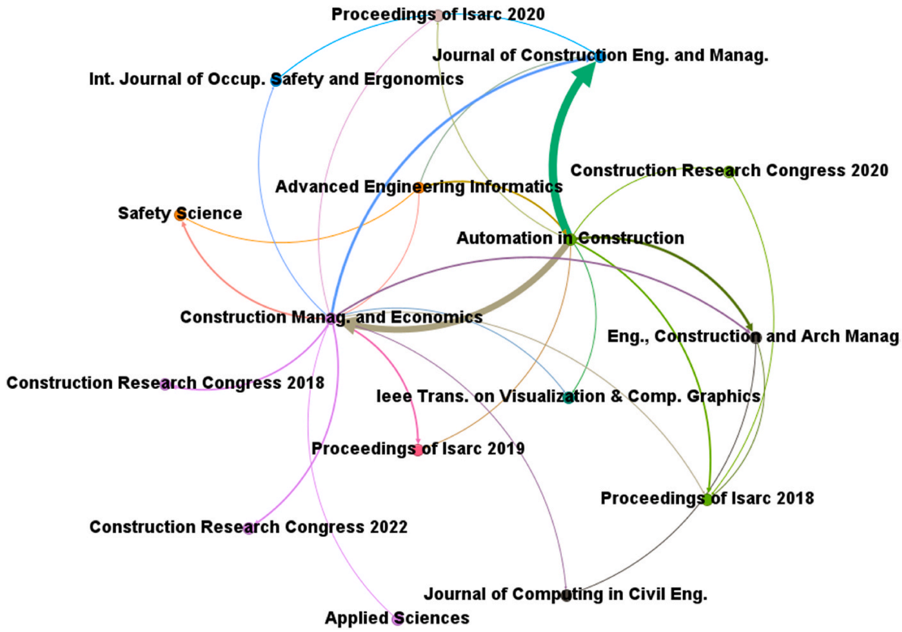

Fig. 5. Science mapping of top publication outlets for VR-CHS domain.

network map of these 16 prominent publication outlets, as shown in Fig. 5. Each node in the map represents a publication outlet, and the edges signify the connections between these outlets based on citation linkages or thematic relevance. The map consists of 16 nodes and 28 edges, depicting the interconnections between the various sources. According to Fig. 5, a strong connection exists between "Automation in Construction" and "Journal of Construction Engineering and Management" likewise "Automation in Construction" and "Construction Management and Economics."

Table 3 ranks the publication outlets using the average normalized citations. This metric ensures that the influence of a publication is not merely assessed by the raw number of citations or the volume of content it publishes but rather by the citations per paper in comparison to a normalized standard. It is especially useful when comparing newer outlets with fewer publications to older and more established ones. According to this metric, the top 5 publication outlets are "Safety Science," "Applied Sciences," "Engineering, Construction and Architectural Management," "Automation in Construction," and "Advanced Engineering Informatics." However, when considering the sheer volume of research output, "Automation in Construction," "Journal of Construction Engineering and Management," "Advanced Engineering Informatics," and "Safety Science," are the most productive.

3.4. Top countries

Understanding which countries are leading or actively participating in specific research areas can offer insights into the global distribution of expertise, investment, and focus on that domain. It also helps identify the potential for international collaborations and the flow of knowledge across borders [45]. The minimum number of documents and citations from a country was set to 2 and 10, respectively. While there is no standardized benchmark for these parameters, the chosen thresholds aim to ensure the inclusion of countries with a significant and impactful scholarly presence. Out of 33 countries represented in the 106 articles, 15 met these criteria. Fig. 6 presents the network mapping of these active countries. The United States emerges as a central node in the network, indicative of its substantial contribution to the field. Its central position reflects a high level of interconnection with many other countries, suggesting robust international collaborations and influence.

Using Gephi, the top 15 countries were ranked using TLS and

Table 3
Top 10 publication outlets in VR-CHS domain.

Publication Outlets	TLS	Documents	Citations	Normalized Citations	Average Normalized Citations
Safety Science	3	4	46	14.5446	3.6361
Applied Sciences	1	2	17	6.9105	3.4553
Engineering, Construction, and Architectural Management	7	3	96	5.5886	1.8629
Automation in Construction	27	14	803	25.7427	1.8388
Advanced Engineering Informatics	5	5	130	8.1745	1.6349
IEEE Transactions on Visualization and Computer Graphics	2	2	45	3.1085	1.5543
Journal of Computing in Civil Engineering	2	3	103	3.5114	1.1705
Journal of Construction Engineering and Management	14	7	241	6.3393	0.9056
Construction Management and Economics	27	3	588	2.4729	0.8243
International Journal of Occupational Safety and Ergonomics	2	2	16	1.2028	0.6014

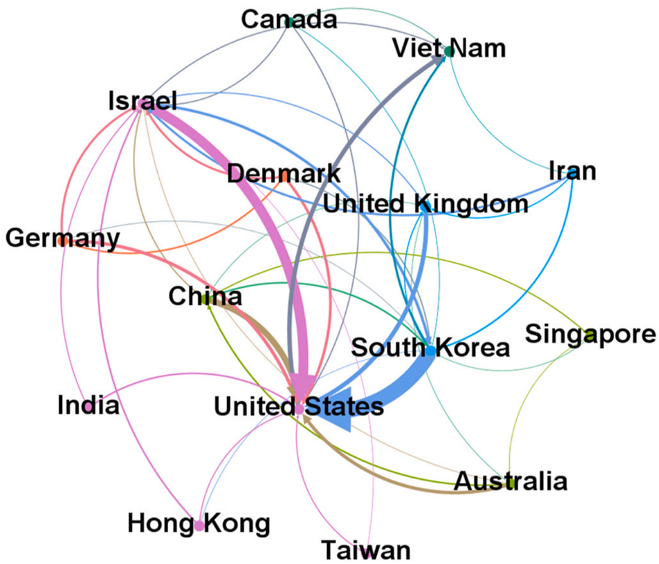

Fig. 6. Network mapping of active countries in VR-CHS domain.

Table 4
Top countries in VR-CHS research areas.

Countries	TLS	Documents	Citations	Normalized Citations	Avg Norm Citations
United States	99	44	1409	53.6019	1.2182
South Korea	51	12	445	16.6195	1.385
Israel	50	2	477	2.0504	1.0252
China	22	13	310	12.6275	0.9713
Viet Nam	16	3	46	1.7274	0.5758
United Kingdom	16	9	133	4.5519	0.5058
Denmark	14	6	86	8.6542	1.4424
Germany	14	9	130	6.2364	0.6929
Australia	12	4	80	3.9341	0.9835
Iran	10	3	37	12.7684	4.2561
Hong Kong	6	5	77	5.5663	1.1133
Canada	6	3	79	3.1386	1.0462
India	5	2	22	1.1	0.55
Singapore	4	2	35	3.7838	1.8919
Taiwan	3	2	11	0.8379	0.419

presented in Table 4. It highlights the importance of collaboration, as countries with higher TLS are likely engaged in more extensive or impactful joint research endeavors, leading to citations across borders. According to this metric, the "United States," "South Korea," "Israel," "China," and "Vietnam" emerge as the top countries, with the "United States" leading not only in TLS but also in the number of publications. This indicates a strong research infrastructure and a significant role in the VR-CHS domain. "China," "South Korea," "United Kingdom," and "Germany" follow suit as productive countries, showcasing their substantial contributions to the field in terms of volume. The presence of "Vietnam," "India," and "Iran" in the list of top countries, despite being developing nations, is notable. It indicates an emerging commitment to research and development within these countries despite the challenges they may face in terms of resources and infrastructure compared to their developed counterparts. The implications are significant; they show a global spread of research activities and the potential for VR-CHS innovation emerging from diverse economic contexts.

4. Result of the systematic analysis

4.1. VR systems in the construction industry

VR systems are defined as complex media systems that utilize specific technologies designed for immersive sensory experience as well as a mechanism of advanced content representation, which has the capabilities of simulation and imitation of imagined and real worlds [47]. According to Buttussi and Chittaro [48], we can access VR via different displays, such as a cave automatic virtual environment (CAVE), a head-mounted device (HMD), or a desktop computer. VR technologies can be classified into five categories: immersive VR (IVR), desktop-based VR (DVR), BIM-enabled VR (BIMVR), 3D game-based VR (3DGVR), and Augmented Reality (AR). This category is based on the various visualization and display media [25]. The study reviews VR-related technology developments and their applications in mitigating various construction hazards. We also have other aspects of VR-related technology, such as software, hardware, interaction issues, and visualization. VR-related technology and virtual environment systems are categorized in detail [49,50].

4.1.1. Immersive VR

IVR utilizes specialized hardware to provide immersive sensory experiences to users. Such hardware includes head-mounted devices (HMDs) and sensor gloves [25]. Waly and Thabet [51] demonstrated IVR by developing the CAVE. Based on the user's location, the user is immersed in a virtual world. The user's position in the virtual environment varies by his/her position in the real world [25]. The degree of immersion is the primary factor distinguishing an HMD and CAVE VR training session from a desktop computer VR training session [52]. According to Cummings and Bailenson [53], immersion describes the degree to which a system can shut out the outside world and offer vivid experiences. The extent of immersion is determined by hardware quality and the amount of senses triggered by the technology. HMD and CAVE VR experiences are commonly considered high immersion [52].

According to Li et al. [24], IVR is a full-immersive VR technology that gives users the maximum level of immersion (the deep sense of being in the virtual world). It is the most expensive system, which takes only 6.7 % of the VR applications in construction safety. One of its key applied areas is in the construction sites' VR walk-throughs to detect hazards [54]. A virtual structural analysis program (VSAP) represents a typical IVR technology designed by the Virginia Polytechnic Institute and State University [55]. VSAP was developed with the intention of investigating building structural behavior within a virtual environment (VE). Notably, VSAP made a significant contribution by introducing an immersive portal interface. This was in response to the high cost of traditional immersive interfaces and the compromise in quality with desktop interfaces, which were more cost-effective. Subsequently, a customized Virginia Tech CAVE (VT CAVE) was designed, featuring a cubic room measuring 3 m × 3 m × 2.75 m. According to Wang et al. [25], it was verified that the VT CAVE had superior effectiveness in terms of usage.

Sacks and Pikas [56] utilized a 3D IVR power wall for the purpose of construction safety training. This power wall setup consists of three rear-projection screens within an open structure resembling a three-area CAVE, employing 3D projection stereo with dynamic glass. Participants engaged in the training using an XBOX controller and a head tracking system, monitored by eight cameras positioned atop the screens. The training employed three distinct software applications: Autodesk Revit was used to model the building displayed in the system, 3D Studio MAX was adopted to model other 3D geometry, and EON Studio v6 was used to generate the VR scenarios. The results indicate that VR-based training improved concentration and gave participants a level of control over the environment. Sacks et al. [54] also adopted similar systems, except for the upgraded version EON Studio V7 for construction safety training. This system satisfies considerable but not all the requirements for a complete IVR environment, as indicated by Ref. [57]. It does not completely prevent all users from observing the physical environment; also, at any one time, only the user wearing the tracker glasses was able to observe the environment from their perspective (the others were unable to control their movement as they were limited to the sense of supporting them).

IVR enables position and head tracking and can render a distinct image for each eye, creating visible signals for deep insight. IVR, compared to a mirror, also improves the scope of the visual area of view. These characteristics are essential for defining the IVR benefits and learning experiences [52]. IVR differs from augmented or mixed reality technology, according to Loomis et al. (1999), in that the former completely isolates the user's mind within the virtual environment and completely blocks out the outside world, while the latter allows the user to experience the real and the virtual environment concurrently.

4.1.2. Desktop-based VR

In the early stages, Digital Virtual Reality (DVR) emerges as the predominantly used VR technology within the realm of construction engineering education and training [25]. Bae et al. [58] assert that DVR is the most cost-effective and least immersive VR system, requiring the least sophisticated components. It can also be called Window on World or Fish tank system. DVR in CHS is commonly applied in training and education. According to Chen et al. [59], DVR technology allows virtual activities to be carried out on a regular computer monitor. It displays a three-dimensional virtual world on a desktop monitor, without the need for extra tracking equipment. DVR depends on the users' perception and spatial capacities to observe what occurs around them. A user can conduct most tasks with DVR technology using keyboards and mice. Relying solely on keyboards, monitors, and mice, DVR is perceived as a cost-effective option in comparison to other VR-related technologies [25].

Notable examples of distinct DVR advancements include V-REALISM, developed by Li et al. [60], and the Interactive Construction Management Learning System (ICMLS), designed by Sawhney et al. [61]. To aid with maintenance engineering training, V-REALISM was created. It creates geometrical models by adopting CAD, which is then displayed via the OpenGL programming platform. It improves interaction and navigation in the virtual world by integrating a ranking system for these models. This is considered the primary noteworthy contribution of V-REALISM [60]. Likewise, ICMLS was designed to manage the disconnect between training and physical on-site activities linked to the construction approaches and equipment. ICMLS is a web-based tool for creating virtual models using VR modeling language (VRML). It displays proper operations through web-based computing and discrete-event simulations (DES) [61]. Mawlana et al. [62] indicated that ICMLS could be engraved into construction engineering education and training as it will enhance on-site construction. DVR development is reasonably stable, with inventions concentrating on virtual laboratories and 3D computer prototypes to motivate students and increase their knowledge [63,64].

4.1.3. BIM-enabled VR

BIM is connected to developing and operating 3D objects, including applicable properties and details [65,66]. The applicable properties and details mainly refer to the critical data needed in realistic building construction throughout its life cycle. This encompasses the planning, designing, construction, operation, and maintenance phases. BIMVR depends on the model, highlighting the links behind different categories of VR and data binding to simulate building operations and activities. One of the essential features of BIM is Visualization [67,68]. BIM data can be accessed in an immersive visualization world, and factors such as material type and cost will be analyzed to create an effective construction design. By examining the design information, all the BIM model components, such as mechanical, electrical, and plumbing (MEP), structure, and architecture, can be considered more detailed [25]. With BIMVR, for example, users may explore the area created, experience the BIM model in a virtual environment without being constrained by gazing at 2D drawings, and take construction designs into a 3D virtual world with all relevant architectural elements.

Users can migrate from the traditional 2D drawing design systems to those in BIMVR virtual world using Autodesk Revit Live. This will help maintain the building management information integrity in the virtual world before the structure is constructed to have a good knowledge of how the design components will materialize [25]. One of the most significant benefits of BIMVR is the model's ability to reflect immediate modifications. Xie et al. [69] indicated that VRML's conventional VR models might have challenges integrating concurrent information. The compatibility issue may cause such difficulties. To further aid in the decision-making process, several strategies have been developed. For instance, Woodward and Hakkarainen [70] created a software system that visualizes construction site activities by integrating schedule information with 3D models. Additionally, Park et al. [71] introduced an interactive building anatomy modeling (IBAM) system, enabling users to engage with building components within a VR environment. Developers can also integrate a fixed question-and-answer game to improve the training experience in its application in CHS.

4.1.4. 3D game-based VR

3DGVR is a game-like computer-based training scenario via interactive, multi-user operating technologies and networks, integrative visuals, etc. It aims to improve interactions among users. The 3DGVR helps students collaborate and interact through tasks relevant to their real-life scenarios [72–75]. Besides concentrating purely on the immersive impact, 3DGVR focuses better on the interactions of game objects. For example, we may use a game engine's physics simulation component to precisely describe collision reactions. To reduce the detection procedures' complexity in 3DGVR, ray-tracing methods and simplified collision boundaries are utilized [25]. It makes collision detection computation easier and reduces complexity for complicated objects like construction cranes and excavators.

Guo et al. [76] created an online platform safety training technology that is game-based, enabling users to adopt input devices, like game controllers, mice, keyboards, etc., to perform virtual activities like material delivery and equipment operation. The primary advantage of the system lies in the cost-effectiveness of having replicated trials readily accessible. For instance, with the adoption of the game-based method, diverse schedules and approaches to operating the equipment can be tested. Testing can uncover potential concerns, such as health and safety considerations [25]. Le et al. [77] designed a game-based training system to manage construction defects. Revit Architecture was used to create the virtual components, and Linden Scripting Language was adopted to represent the close-to-reality defect scenarios. In this system, the trainees were taught based on their knowledge of construction defects. They were given various scenarios and asked to pinpoint defects and likely tasks that could cause them. The test showed positive outcomes in terms of performance and interactivity [25].

4.1.5. Augmented reality

The AR system, which accounts for 32 %, is applied in the instruction and inspection process in VR applications in construction safety. In adopting this system, real-world objects are utilized as AR interface components, and their manipulation is adopted for virtual content interactions [78]. Collaborative AR, as defined by Kim et al. [79], involves participants sharing an environment that contains both virtual and real-world items. In that manner, the interactions are among users, not just between the AR system and a user. AR provides a direct or indirect image of a real environment by utilizing sensory technologies, incorporating video and sound alongside AR information. According to Fonseca et al. [80], people find it easier to interact with AR objects and change their location, attributes, and scale, in a manner that seamlessly aligns with the real world, as opposed to a VR setting. Consequently, multiple studies have asserted that AR systems have the potential to introduce new interaction possibilities and enhance active students' engagement [81–84].

For instance, Chen et al. [85] adopted ARToolKit to create an AR system to teach students about their capacity to identify spatial objects. Diverse 3D models may be projected onto the real world via the AR system, contributing to the enhancement of students' education [86]. Additionally, a number of apps have been created to incorporate AR into mobile devices, taking advantage of the evolving nature of mobile gadgets to facilitate learning [25]. For example, Williams et al. [87] provided training in context awareness through a mobile AR (MAR) environment. Shirazi and Behzadan [82] developed the CAM-ART mobile context-aware AR tool for an undergraduate course in construction engineering. In the CAM-ART AR system, the interactions between objects are defined using JavaScript logic, while the content definition was realized using a static extensible markup language. To improve the process of construction, Kim et al. [79] designed an AR-based system by modifying how equipment is being operated. The benefits of AR in this study are that the system improves visualization from the users' viewpoint, and they can identify surrounding constraints.

4.2. VR and construction health and safety

VR-based simulation provides users with an immersive experience to gain insights into how the real-world works [88]. With VR, users perceive the outside world through a computer-generated 3D environment instead of seeing the outside world in its natural state (Li., et 2018). Virtual Reality (VR) enables users to pay close attention to and employ appropriate strategies for diverse scenarios arising from various hazards present on construction sites [67]. Jeelani et al. [89] similarly highlighted the efficacy of incorporating a VR training approach for construction professionals, emphasizing that this experience enhances the users' learning process. According to the study, after the participants were interviewed, they recognized that it was a highly realistic and engaging experience they had experienced something engaging and realistic during the appropriate testing. VR has an established prospect of providing training for hazardous work specializations by enabling users to simulate duties while avoiding being vulnerable to disorganized job sites [8]. Using a Wii game controller, Li et al. [74] created a multi-user VR training exercise to teach users how to safely dismantle cranes. Dickinson et al. [72] investigated a VR serious game that concentrated on safety in the trench, particularly on caught-in, struck-by, and fall hazards. A highly interactive VR game developed by Guo et al. [76] allows numerous user trainees to complete construction tasks in a virtual setting. The online platform focused on specific construction tasks, especially tasks that have to do with towers and mobile cranes. Zhao et al. [90] developed a VR technology where users conduct a site survey to detect electrical-related hazards.

The use of VR in advancing safety practices has reached the extent that health and safety managers approve of it [29]. The use of virtual drills, health and safety scenarios, and instructions provide CHS training for proper health and safety work experience and an opportunity to examine and modify existing safety orders [91,92]. A study conducted by Shi et al. [93] regarding VR's performance as a construction safety tool acknowledged its effectiveness in safety studies. In 2015, Bhoir and Esmaeili reviewed the use of VR in construction safety. The study located the purpose, proponents, and advantages of using VR to advance on-site safety. In Pedro et al. [94] study, a VR platform was developed and tested to teach AEC students about construction-related dangers. Time and costs were the main challenges associated with VR development.

As for safety awareness applications of VR, Park and Kim [5] propose a system that integrates BIM, AR, game technology, and location tracking. The system improves laborers' real-time communication skills in hazardous environments, providing rich and influential safety practices and knowledge of awareness. Clevenger et al. [95] evaluated the use of 3D visualization in construction industry safety training. Their findings concluded that the integration of virtual construction safety training with BIM proved advantageous for undergraduate students. Sacks et al. [96] used VR as a tool by which designers and builders communicate, which serves as a forum to learn and proactively design change to enhance the building of a safer project. The study indicated that consultation and conversations via VR helped designers in taking safety into account during the construction process. Côté and Beaulieu [97] developed a conceptual modeling of hand gestures-based VR road and construction site safety, where an instinctive hand gestures VR road plan application was launched and established. The study revealed that the comfortable VR-driven system they invented offered an "easy, fun, and natural to use" and can evolve into a user-friendly and laid-back substitute for complicated 3D engineering design software.

To obtain real-time data for C.H.S., Cheng and Teizer [98] created a system that included data collecting and real-time visualization in the construction domain. This system suggests that crucial health and safety data can be visualized and monitored to enhance the situational awareness of workers. Goulding et al. [99] concentrated on training construction managers to enhance decision-making from the early stage. Students who participated in the testing experienced a better learning adventure and a realization of real-world scenarios from the viewpoint of a construction manager. Nakai et al. [100] introduced a virtual environment simulating a chemical plant, enabling operators to undergo experiences involving explosion accidents and fires in a digital realm. The authors asserted that this virtual setting assists trainees in comprehending proper tool usage and executing procedures to minimize errors and avert casualties. Similarly, Nazir et al. [101] proposed a research in the oil and gas industry, employing an IVR system in a plant simulator to train participants in hazard detection and prevention. The findings demonstrated that trainees who used the virtual plant simulator showed a higher likelihood of identifying and preventing hazards in real-world situations.

4.3. VR-CHS application domains

4.3.1. Identification and monitoring of construction hazards

Most traditional safety performance indicator estimation techniques are manual and based on arbitrary assumptions [102,103]. These methods depend on big manual data-collecting actions; thus, data are gathered at a lower frequency (for example, once a month) and whenever incidents are recorded [104,105]. These methods are costly and produce extremely little data sets for adequate and successful project control, and are prone to data entry mistakes [103]. Identification of hazards is based on conventional origins on drawings, desktop concepts, heuristic knowledge, and accident cases reported. These methods are being adopted to design preventive measures against anticipated safety hazards via project meetings [7].

To surmount the challenges of these manual activities, VR environment modelling, and visualization emerged to identify hazards that improve users' interactive and immersive experience [106,107]. Continuous construction site safety monitoring through an automated system is increasingly regarded as a highly effective method for ensuring ongoing safety compliance [108]. The construction managers who will act upon the data may immediately access it after the automated monitoring system has collected it and formatted it into a structured manner [109]. VR technology that identifies hazards on-site helps construction workers avoid dangerous zones. Most hazard avoidance systems use real-time tracking, which alerts workers of dangerous areas and approaching equipment; meanwhile, hazard identification systems focus on developing personal identification skills (Moore and Gheisari, 2019).

According to Moore and Gheisari [21], on-site construction hazard monitoring incorporates VR systems with location trackers, providing workers with direct and valid safety information. For instance, Kim et al. [110] designed an AR system that augments the view of workers utilizing the real-time tracking and Google Glass system. Workers were visually notified while approaching equipment, and equipment operators were made aware of their presence. Cheng and Teizer [98] investigated how construction workers' situational awareness may be enhanced by combining real-time tracking with virtual reality technology. Construction personnel and equipment locations were tracked using radio-frequency identification (RFID) tracking devices, and the data was shown in a virtual environment. The prototype analysis revealed positive outcomes; the authors believed that with such technology, workers could evade construction site hazards and be trained in how the virtual environment works by adopting "close call" simulations.

Li et al. [111] adopted VR and real-time tracking for safety and efficiency training. Pre-defined hazard zones and RFIDs helped workers by alerting them with a beep from their hardhats when moving close to heavy machinery or entering a dangerous zone. Furthermore, equipment and workers' real-time locations, which managers and safety professionals could monitor, were represented in a virtual environment called the "Virtual Construction Simulation System." The authors argued that AR is essential for the future of construction training and danger detection, claiming that real-time data visualization displays a limited amount of realism. Zhou et al. [30] investigated the use of 4D visualization in detecting safety threats as they changed throughout the course of an underground metro construction project, based on a lifecycle study of the project. Data and risks were numerically analyzed using the 4D visualization and mathematical equations. The results of the study indicate that the project's detection of safety threats is facilitated by real-time information tracking and visualization. However, it was noted that risks and building sites are ever-evolving, making it challenging to manage this inherent aspect using the suggested method.

4.3.2. Construction safety education training

Safety education and training effectively improve safety control [112]. This generally constitutes on-site and off-site training. While off-site training does not provide employees hands-on learning opportunities, on-site training is inefficient and can cause disruptions to routine construction work, which lowers production. VR can enhance safety education and training by furnishing visualized data and providing hands-on training in virtual off-site [23]. Even though on-site safety training can be more effective [94] because it involves hands-on experience and direct involvement, it can be time-consuming, expensive, and even dangerous due to actual site circumstances, such as schedule clashing, access problems, weather conditions, overriding safety concerns, and liability issues [113]. VR technologies provide unique opportunities for efficiently educating and training students or novices with higher cognition levels and lower risks.

The usage of various kinds of VR in workers' training is rampant. Aviation simulators are a famous example, and VR is efficient for training in road safety [114]. VR simulation training for medical operations is also common because it evades the intrinsic risk of training on humans and other living creatures [115]. A number of technologies, such as gaming, VR, AR, and BIM, have been created to enhance construction safety education and training procedures. For instance, Pedro et al. (2015) designed a QR code-scanning technology to provide safety information to university students using smart devices. Although developing the VR elements and classifying the safety details is deemed time-consuming, the results are encouraging. Students' inspiration and attention to learning are developed in VR-related training.

Training on-site is difficult due to its hazardous nature, and failure on construction sites certainly eliminates the possibility of training. Construction sites training facilities, such as those in the Netherlands, UK, and Australia, can be built specifically to simulate construction environments [116]. VR technologies present the chance to enlighten workers about accidents and risky situations as part of construction safety training, as seen in Fig. 7. Workers can evaluate a problem, determine the action to take, execute the action, and instantly monitor the outcomes. This leads to psychological information handling, which stays in the memory for a long time. Lucas et al. [117] study on safety education for construction equipment operators stands out as one of the limited instances where VR has been utilized for education and training in construction safety. An other example is ForgeFX [118], a general VR industrial safety teaching game developed for the California State Compensation Insurance Fund that includes a component that replicates handling materials to build a timber roof for a house. Ku and Mahabaleshwarkar [119] suggested the prospect of adopting 'Second Life' in construction safety education and training and the countless issues.

Perdomo et al. [121] state that several research have investigated VR as an addition to traditional construction education and training. Sampaio et al. [122] investigated the applicability of CAD, VR, and 3D modeling in AEC education. A 3D game that let college students assume the role of safety inspectors and assess potential hazards at work sites was the subject of Lin et al.'s [123] investigation. Li et al. [74] also designed a 4D Interactive Safety Assessment, a unique safety-evaluation technique that used virtual scenarios to evaluate construction personnel. The mechanism offered workers virtual hazard conditions linked to their tasks and a spectrum of potential activities of choice. In order to help students comprehend health and safety in trenches, Dickinson et al. [72] developed a serious game that allows them to explore the 3D world. Michael [124] defined serious games as games with the main purpose of education instead of entertainment. Based on the evidence from the literature, the adoption of VR in construction safety education and

Fig. 7. VR application in construction safety education and training [120].

training and the understanding of their usage and efficiency is limited. Some of the issues for researchers have been the substantial expenditure needed to organize the IVR system, including pedagogical and animation elements, the 3D scenery, and the demand to get construction workers to a specified facility [54].

4.4. Challenges associated with VR applications in CHS

There is no argument that VR possesses enormous prospects for promoting CHS efficiency. It is a promising tool for improving CHS [125]. Literature indicates that despite VR-CHS's excitement and hype, the system faces some challenges [125,126]. These challenges include infrastructure, algorithm development, virtual content modelling, general health and safety, and interoperability, as highlighted in Table 5.

4.4.1. Infrastructure

Challenges associated with the device's weight can negatively impact its acceptance by users, which will hinder the broader VR adoption [125]. According to Yan et al. [127], as the HMDs' weight increases, the pressure load and the users' subjective discomfort increase. HMDs' weight has been linked with visual discomfort and related injury experiences, as noted by Yuan et al. [128]. Similarly, several studies have highlighted the substantial influence of view angle [129] and display brightness [130] on the level of immersion and the user's task performance. Despite these challenges, it is suggested that HMD developers can overcome these challenges without compromising processing capabilities, thanks to advancements in the current chip revolution. The resolution of these challenges is anticipated in the coming years [131].

4.4.2. Algorithm development

In contrast to industries like automobile and manufacturing, where standardized processes are more common, every construction project is unique, with distinct requirements from stakeholders. Consequently, customized algorithms are essential for each construction project to ensure that the virtual world and associated systems align with the specific needs of the stakeholders. Besides, developing an immersive, interactive, illustrative, intuitive, and informative virtual world needs a particular skill set; this is referred to as one of the challenges in the literature [125]. As the construction sector is encouraging a more accurate and efficient process, there is a precise need for construction professionals to update their programming skills constantly. Given the existing shortage of skills in the construction sector, as highlighted by Sawhney [132] and Liu et al. [133], there is a pressing need for the industry to attract a skilled workforce. Failing to do so may result in the sector relying on third-party developers to supply virtual content, potentially leading to cost overruns.

Table 5
Challenges facing VR applications in CHS.

Challenges	Descriptions
Infrastructure	Challenges that hinder VR technology deployment result from hardware issues such as view angle, resolution, device weight, unrestricted user mobility, portability, device ergonomics, ease of deployment, frame rate, and dedicated space requirements.
Algorithm development	Programming issues and the demand to provide immersion and interaction by developing bespoke scripts appropriate for the VR-CHS.
Virtual content modelling	Issues related to virtual content development that will be adopted to create immersive visualization.
General health and safety	Health and safety-related problems that may cause mishaps and illness, including anxiety, crashing into physical objects, electromagnetic exposure, dizziness, eye strain, and nausea.
Interoperability	The VR-CHS's various modeling tools' capacity to transport data into the virtual world's development engines without requiring several iterations.

4.4.3. Virtual content modelling

Creating VR content that is genuinely inviting and captivating is a challenge that demands a significant skill set and funds. This challenge may not be as vital for those companies that have embraced BIM workflow as it is for other companies that are just aspiring to adopt BIM. While BIM models undergo multiple iterations before being imported into a virtual world, the extensive tasks involved in building modeling can be efficiently executed using BIM authoring tools integrated into BIM products. Users may integrate BIM models straight into the Unity game engine with the use of contemporary software tools like Unity Reflect. However, it's worth noting that additional efforts are required for material enhancement, behavior assignments, and post-texturing, which can be resource- and time-consuming activities [125]).

4.4.4. General health and safety

General health and safety challenges related to VR, like physical (unnatural postural demands, immersion injuries, hygiene), physiological (convergence cardiovascular changes, visual asthenopia signs, and symptoms), and psychological (change in psychomotor performance, addiction, stress), are significant problems while utilizing these technologies [134]. Any potential VR user in the VR-CHS must choose the technology based on this specific task and comprehend the possible health and safety implications related to the system. Nevertheless, users should pay attention to these technologies' health and safety guidelines provided by the manufacturers and ensure they comprehend them. Also, a sequence of undesirable symptoms like headaches and nausea are usually the immersive environment side effects [135]. According to Prabhakaran et al. [125], it is anticipated that most of these challenges could be alleviated with the wireless connectivity between computers and HMDs, advancements in display quality like OLED, locomotion methods adopted like teleportation, and lightweight hardware.

4.4.5. Interoperability

The optimization of the VR-CHS process greatly depends on addressing the critical issue of system interoperability in virtual world development game engines such as Unity 3D and Unreal Engine [136]. Middleware has been employed by several software providers, including Unity (unity3d.com), to bridge this gap recently [137]. Nevertheless, these developments need additional iterations and improvements using middleware applications as they are still in their infancy. Further, with the Unity Reflect introduction [138], facilitating an immersive experience has become unchallenging with the BIM models' transfer jointly with their meta-data into the Unity game engine. However, developing interaction, which demands tailored algorithms, remains challenging.

5. Existing gaps and future directions

Following the literature review presented in the previous sections, some gaps are identified, and recommendations to fill them are proposed. Fig. 8 summarizes the gaps and future directions.

5.1. Limited studies on health and safety learning within VR and the human factors

Human error plays a pivotal role in safety hazards, contributing to near misses, casualties, and serious incidents. However, only a limited number of studies have delved into the discussion of human error. In general, human error is related to several things. According to Visser et al. [139], one of the main factors causing accidents in civil work excavation is distraction. A virtual environment was developed with the goal of addressing "cognitive distraction," which causes operators to overlook environmental cues like warning lights, which can lead to safety accidents. Abdelhamid and Everett [140] demonstrated that workers' negligence and a lack of attention to detail are the most

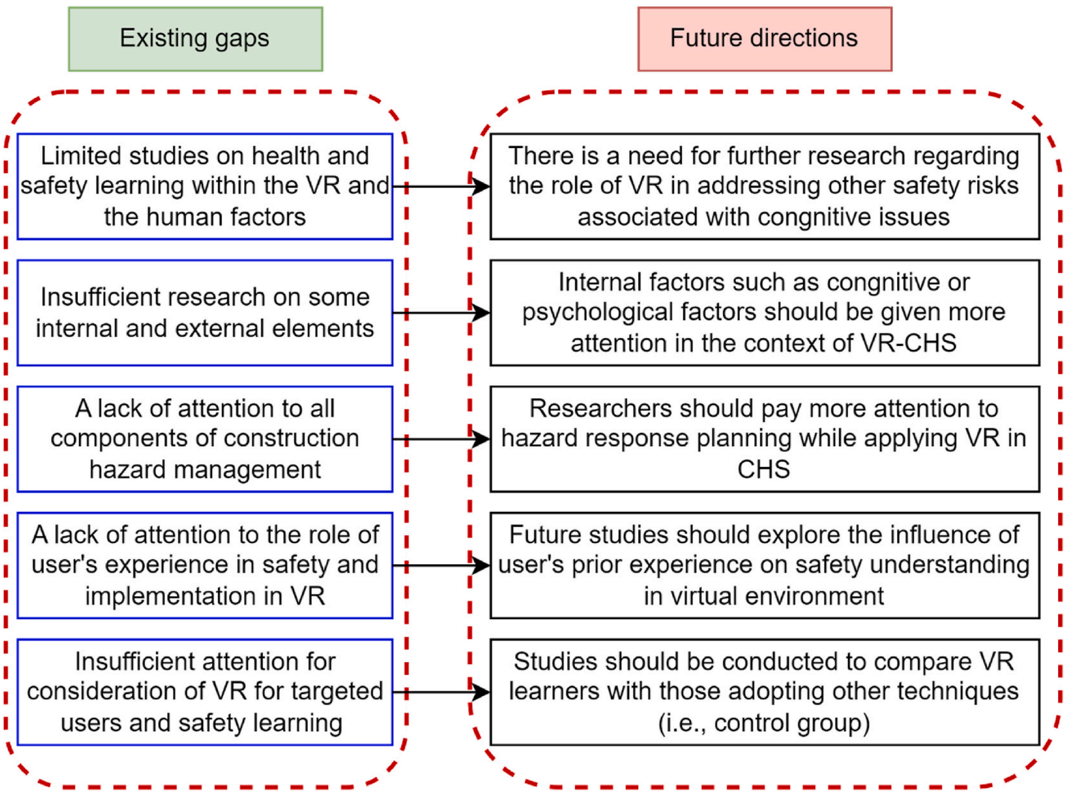

Fig. 8. Existing research gaps and future research directions.

commonly responsible for human errors. Addison et al. [141] and O'Hare and Addison [142] claim that many accidents are caused by human factors linked to insufficient competences. Engineering industry personnel need a high degree of training and competence to operate safely and evade disastrous casualties [143].

Although competences were not clearly defined, the studies analyzed in the literature review focused on the skills and competence aspect of addressing the issue of safety risks in the engineering and construction sectors. Thus, more investigation is required to determine how VR can reduce additional safety hazards related to cognitive problems like distractions. VR has indeed contributed to reducing human errors in other fields. In the aviation industry, virtual simulation systems, for example, have reduced serious incidents by handling human error [144]. Experience gained from other technical sectors, such as the aviation industry, can be applied to the construction and engineering industry. This is particularly relevant since human error is identified as a potential and significant hazard in both sectors.

5.2. Insufficient research on some internal and external elements

Studies related to external factors, such as severe climate conditions that can jeopardize CHS, are largely insufficient. Thus, studies on how technology could enhance the mitigation of safety hazards due to unforeseen and observed occurrences, such as dangerous climate conditions, are not enough. BIM and sensors could be beneficial in satisfying such significant issues. Furthermore, studies have not sufficiently addressed internal elements impacting workers, such as cognitive or psychological components, despite the potential for VR to enhance these facets. This highlights a research gap, suggesting the need for future studies utilizing IVR technologies to enhance individual safety by incorporating inputs based on psychophysical information.

5.3. A lack of attention to all components of construction hazard management

Existing research predominantly emphasizes the early stages of construction hazard management, particularly hazard identification and assessment. This focus is evident in studies like those conducted by Guo et al. [145], Cheng and Teizer [98], Carozza et al. [146], Dawood et al. (2014), and Li et al. [111], which have developed virtual environments aimed at training construction personnel in hazard detection. However, there is a notable gap in addressing the latter stages of the hazard management cycle, especially in the context of hazard response planning. This phase, critical for effectively mitigating and managing hazards on construction sites, has received comparatively limited attention in scholarly research. As a result, there is a need for future studies to explore and develop comprehensive strategies that encompass all aspects of construction hazard management, including the development of robust response plans. This will ensure a more holistic approach to safety in the construction industry, addressing the recognition of hazards and the preparedness and response mechanisms to deal with them effectively.

5.4. A lack of attention to the role of users' experience in safety & implementation in VR

The VR studies examined have not finalized whether the prior experience and safety understanding level impact the learning results within a virtual environment. In contrast to student participants in comparable studies, Perlman and Sacks's [147] study on risk identification highlighted that construction superintendents are well trained to assess dangers on construction sites. According to Dawood et al. (2014), prior safety knowledge has little bearing on how well people learn to recognize risks in virtual environments. This study, however, did not contrast how well students performed in the actual and virtual worlds. Perlman and Sacks [147], on the other hand, compare students' risk recognition skills in the virtual world, the traditional project papers (which include schedules, photos, and drawings), and they demonstrate that learners' hazard detection skills are more satisfactory in the virtual world. A study by Nickel et al. [148] also showed that submerging the construction personnel in the virtual world without risk improves the workers' perception of hazards once they return to the physical environment. This can influence the general safety performance of the project and the workers' ability to recognize hazards before they turn into harmful events, which aids the deterrence of numerous casualties [149]. The significance of prerequisite knowledge and learning before venturing into a fresh journey of learning is well-known in education theory. Future VR study is recommended to explore this notion increasingly, even though it may be difficult to determine the 'prerequisite' idea for VR learning. Nevertheless, a practical method of testing with diverse learner groupings and using control groups may deliver good insights.

5.5. Insufficient attention to consideration of VR for targeted users and safety learning

In the construction industry, safety learning is crucial for a broad range of participants, including existing professionals like managers, engineers, safety officers, laborers, and future professionals, namely students pursuing construction engineering education in universities and colleges. While some studies have addressed the needs of these distinct groups regarding safety learning via VR, there remains a significant oversight. Research such as that conducted by Xie and Carr [150], Dickinson et al. [72], Lin et al. [73], Greuter et al. [151], and Dawood et al. (2014) has explored VR's impact on safety learning among tertiary education students. Conversely, other studies have focused primarily on industry professionals.

However, a gap exists in the comparative analysis of VR's effectiveness. Only a few studies, such as those by Sacks et al. [54] and Perlman and Sacks [147], have employed control groups to compare the safety performance outcomes between VR-trained individuals and those trained via alternative methods. The establishment of such comparative data is essential for validating and reinforcing the adoption of VR in safety training within the construction sector. It's necessary for future research to focus on generating this evidence, as it can significantly enhance the strategic implementation of VR in safety education, catering effectively to the specific learning needs of both current and future construction industry professionals.

6. Conclusion

This investigation synthesizes VR-CHS research through a combined scientometric and systematic review. Scientometric analysis, detailing publication trends, keyword co-occurrence, influential outlets, and active countries, reveals the field's expansion and thematic networks. The scientometric analysis reveals significant insights into the research landscape of VR applications in CHS. The annual publication trend shows a steady increase in research output, highlighting growing academic and industry interest in this field. Keyword co-occurrence analysis identifies core topics such as "virtual reality," "construction safety," "hazard identification," "risk assessment," "VR training," and "immersive environments." Analysis of publication outlets shows that prominent journals such as "Automation in Construction," "Journal of Construction Engineering and Management," "Advanced Engineering Informatics," and "Safety Science," frequently publish articles on VR in CHS, underscoring their role in disseminating relevant research. Additionally, the contributions from leading countries, including the "United States," "South Korea," "Israel," "China," reflect a strong international collaboration and a diversified research effort aimed at enhancing construction safety through VR technologies.

The systematic analysis provides a comprehensive examination of various VR systems utilized in CHS, including immersive VR, desktop-based VR, BIM-based VR, game-based VR, and augmented reality technologies. Each of these systems is evaluated for its effectiveness in hazard identification and safety training. For instance, Immersive VR is highlighted for its high realism and user engagement, making it particularly effective for experiential learning and hazard recognition. Desktop-based VR, although less immersive, offers accessibility and cost-effectiveness, proving useful for basic safety training and procedural tasks. The systematic review also identifies key challenges associated with the implementation of VR in CHS, such as infrastructure limitations, issues with content modeling and interoperability, and health concerns related to prolonged VR usage. Addressing these challenges is crucial for the broader adoption and effectiveness of VR technologies in the construction industry.

The synthesis of the literature reveals research limitations, particularly in safety learning within VR environments and the influence of cognitive factors on safety practices. The study advocates for research tailored to users' experiences, stressing the need to understand how prior safety knowledge affects learning in VR. The relationship between users' pre-existing safety understanding and VR learning outcomes remains under-investigated, presenting a complex but critical area for future exploration. The findings underscore the necessity for more nuanced research into VR's role in managing safety risks and addressing the psychological and environmental aspects of construction hazard management. The study calls for greater attention to how VR can enhance safety education for specific user groups. It recommends further inquiry into the user's experience in VR safety training and the integration of VR into practice, despite the challenges in assessing VR learning prerequisites.

While this study provides a scientometric and systematic review of VR applications in CHS, some limitations need to be acknowledged. The scientometric analysis is dependent on the availability and accuracy of publication databases, which may not capture all relevant studies, especially those published in non-English languages or less accessible journals. This could result in a potential bias in the representation of global research efforts and trends. Additionally, the keyword analysis might miss emerging topics that are not yet well-represented in the literature but could be significant in the near future. The systematic review primarily focuses on the technological and methodological aspects of VR systems without extensively exploring the practical implementation challenges faced by the construction industry. The study's recommendations, while strategic, are based on the existing literature and may not fully account for real-world constraints such as financial limitations, resistance to technological change, and varying regulatory environments across different regions. Future research should aim to conduct empirical studies and field trials to validate the effectiveness of VR applications in diverse construction settings and address these practical challenges comprehensively.

CRediT authorship contribution statement

Nelson Akindele: Writing – review & editing, Writing – original draft, Project administration, Conceptualization. **Ridwan Taiwo:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Hadi Sarvari:** Writing – review & editing, Visualization, Formal analysis. **Benjamin I. Oluleye:** Writing – review & editing, Formal analysis, Data curation. **Imoleayo A. Awodele:** Writing – review & editing, Conceptualization. **Temitope O. Olaniran:** Writing – review & editing, Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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