

Mapping Research Trends, Collaboration Networks, and Emerging Themes of Virtual Reality in Construction Safety Management: A Bibliometric Analysis

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Abstract

Virtual Reality (VR) has become an increasingly important technology for improving construction safety by enabling immersive training, hazard identification, and interactive learning environments. As research in this area has expanded rapidly, understanding its intellectual development, collaboration patterns, and emerging research directions has become increasingly important. This study presents a bibliometric analysis of research on VR applications in construction safety management using publications indexed in the Scopus database between 2000 and 2024. A dataset of 432 documents was analysed using the Bibliometric package in R and VOSviewer to examine publication trends, citation performance, collaboration networks, keyword co-occurrence, and thematic evolution. The findings indicate substantial growth in scientific output, particularly after 2018, reflecting the increasing adoption of digital technologies within the construction industry. The analysis identifies the leading authors, institutions, countries, and publication sources that have shaped this research domain, while revealing four dominant thematic areas: VR-based safety training, BIM-enabled digital integration, human factors and user experience, and intelligent safety systems incorporating artificial intelligence and related technologies. The results further demonstrate a gradual transition from visualisation-oriented applications toward integrated, data-driven, and human-centred approaches to construction safety management. By providing a comprehensive overview of the field's intellectual structure and research evolution, this study highlights current knowledge gaps and identifies promising directions for future research, including AI-assisted VR systems, digital twins, and adaptive immersive training environments. The findings offer useful insights for researchers, practitioners, and policymakers seeking to advance the implementation of VR technologies in construction safety management.

Keywords: Virtual Reality (VR), Construction Safety Management, Bibliometric Analysis, BIM Integration, Research Trends

1 Introduction

The construction industry continues to experience one of the highest rates of occupational accidents and fatalities worldwide, making effective safety management a persistent priority for both researchers and practitioners. Although regulatory requirements and safety training programmes have contributed to improving workplace safety, construction projects remain highly dynamic environments where workers are frequently exposed to changing hazards, complex tasks, and unpredictable site conditions. Conventional safety training

approaches, including classroom instruction, printed guidelines, and on-site demonstrations, often struggle to recreate realistic hazard scenarios or actively engage trainees. As a result, the transfer of safety knowledge from training environments to real construction sites remains a significant challenge. Recent advances in digital technologies have created new opportunities to address these limitations. Among these technologies, Virtual Reality (VR) has emerged as a promising approach for delivering immersive and interactive safety training. By enabling workers to experience realistic construction scenarios in a controlled virtual environment, VR supports hazard recognition, decision-making, and experiential learning without exposing participants to actual risks. Consequently, VR has attracted increasing attention from researchers, industry professionals, and policymakers seeking more effective approaches to improving construction safety performance and reducing workplace accidents.

The growing adoption of VR has been accompanied by a substantial increase in academic research investigating its applications in construction safety management. However, despite this rapid expansion, the existing body of literature remains fragmented in several important respects. Most previous studies have concentrated on evaluating specific applications of VR, such as safety training, hazard recognition, or the integration of VR with Building Information Modelling (BIM). While these investigations have generated valuable insights into the effectiveness of individual technologies and training approaches, they provide only a partial understanding of how the research field has evolved as a whole. Another important limitation is the lack of comprehensive quantitative assessments of the intellectual structure of this research domain. Existing review studies are predominantly narrative or systematic in nature and rarely examine publication dynamics, collaboration networks, influential contributors, or the evolution of research themes using bibliometric techniques. Consequently, there is still limited evidence regarding how scientific collaborations have developed, which research topics have gained prominence over time, and where emerging research opportunities are likely to arise. To address these limitations, this study employs a bibliometric approach to systematically map the development of VR research in construction safety management between 2000 and 2024. By combining publication trend analysis, citation analysis, collaboration network visualisation, keyword co-occurrence analysis, and thematic evolution mapping, the study provides a comprehensive overview of the field's intellectual landscape. Accordingly, a comprehensive bibliometric assessment is needed to systematically evaluate the development, knowledge structure, and future direction of this rapidly evolving research field.

Beyond identifying publication trends, this study seeks to provide a comprehensive understanding of the evolution of VR research in construction safety management from multiple perspectives. Unlike previous review studies that primarily summarise existing findings, the present research integrates bibliometric performance analysis with science mapping techniques to reveal the intellectual structure of the field, collaboration patterns among researchers and institutions, and the evolution of major research themes over time. The findings are expected to assist researchers in identifying emerging research opportunities, support practitioners in understanding technological developments, and provide evidence that can inform future research agendas and decision-making related to digital safety management in the construction industry. The findings of this study are expected to provide valuable insights for researchers, practitioners, and policymakers seeking to better understand the evolution of VR technologies in construction safety management and identify promising directions for future research. To achieve these objectives, the following research questions were formulated to guide the bibliometric investigation.

1. What are the major publication trends in VR-related construction safety research?
2. Which authors, institutions, and countries have contributed most significantly to this domain?
3. What are the dominant research themes, clusters, and knowledge structures emerging from the literature?
4. What future research directions can be derived from the identified trends and gaps?

By addressing these questions, this research provides an in-depth understanding of the academic evolution and current landscape of VR in construction safety. The results aim to guide scholars, practitioners, and policymakers in advancing both theoretical and practical aspects of safety management through digital transformation.

2 Literature Review

2.1 Virtual Reality in Construction Safety

Virtual Reality (VR) has emerged as one of the most influential digital technologies for enhancing construction safety by creating immersive environments in which workers can experience realistic job-site conditions without being exposed to actual hazards. Unlike conventional safety training methods, which often rely on classroom instruction, videos, or static demonstrations, VR provides interactive three-dimensional simulations that enable users to recognise hazards, practice safety procedures, and make decisions within dynamic construction scenarios. Earlier studies by Albert et al. (2014) demonstrated that immersive VR environments combined with cognitive learning strategies significantly enhance hazard recognition and safety communication among construction workers. This experiential learning approach not only increases trainee engagement but also improves knowledge retention, risk perception, and hazard-recognition capabilities (Albert et al., 2014; Babalola et al., 2023). Overall, recent systematic reviews consistently indicate that immersive technologies have become an integral component of construction safety management by improving training effectiveness, hazard awareness, and worker engagement (Babalola et al., 2023). The application of VR in construction safety has evolved considerably over the past two decades. Early research primarily explored the technical feasibility of implementing virtual environments for construction education and safety visualisation, with development constrained by limited computational resources and the relatively high cost of immersive hardware. As VR technologies became more accessible and sophisticated, research gradually shifted from technology-oriented development toward evaluating user experience, learning effectiveness, cognitive performance, and behavioural responses during safety training. This transition reflects a broader movement from demonstrating technological capability to assessing how immersive technologies can meaningfully improve safety outcomes in construction practice. More recent studies have confirmed the effectiveness of VR as an educational and decision-support tool within construction safety management. Fang et al. (2020) demonstrated that immersive VR training significantly improves workers' ability to recognise hazardous situations and respond appropriately, thereby reducing the likelihood of human error. Jeelani et al. (2020) further demonstrated that immersive virtual reality and stereo-panoramic environments enhance hazard recognition skills by providing realistic construction scenarios that improve workers' engagement and learning effectiveness. Other researchers have extended this perspective by incorporating behavioural assessment, real-time feedback mechanisms, and gamification strategies into VR-based learning environments. Collectively, these studies indicate that VR has progressed beyond a visualisation technology to become an integrated platform for developing safety competencies, supporting behavioural change, and promoting proactive risk management throughout construction projects. Similarly, Rokooei (2020) reported that immersive VR-based training enhances workers' perception of construction risks and supports more informed safety-related decision-making during hazardous tasks.

2.2 Integration of VR with Digital Construction Technologies

The rapid digital transformation of the construction industry has significantly expanded the role of Virtual Reality beyond stand-alone safety training applications. Increasingly, VR is being integrated with complementary digital technologies to create comprehensive environments that support planning, monitoring, decision-making, and risk management throughout the project lifecycle. This integration enables safety information to be visualised within realistic virtual environments, allowing project stakeholders to identify hazards, evaluate alternative construction scenarios, and implement preventive measures before work begins on site.

Among these technological developments, the integration of BIM and VR has received considerable attention. BIM provides detailed digital representations of construction projects, while VR transforms these models into immersive environments that facilitate interactive visualisation and safety assessment. By combining these technologies, engineers, designers, and safety managers can conduct virtual site walkthroughs, identify potential conflicts, evaluate hazardous work sequences, and improve communication among project participants. Previous studies, including those by Sacks et al. (2015) and Li et al. (2018), have demonstrated that BIM–VR integration enhances spatial understanding, collaborative decision-making, and proactive safety planning, ultimately contributing to improved construction safety performance. More recently, research has expanded toward integrating VR with emerging technologies such as AR, the IoT, AI, and Digital Twins. Recent studies also highlight the growing role of Digital Twin technology in integrating real-time construction data with immersive virtual environments, enabling dynamic safety monitoring and predictive risk assessment throughout project execution (Luo et al., 2024). The combination of VR and Digital Twin technologies is expected to support intelligent construction management by linking physical construction processes with continuously updated virtual representations of project conditions (Zhang et al., 2023). These technologies extend the capabilities of immersive environments by incorporating real-time monitoring, sensor-generated information, predictive analytics, and intelligent decision support into safety management processes. AI-enabled VR systems, for example, can evaluate user performance during training sessions, adapt scenario complexity according to individual learning progress, and provide personalised feedback to improve training effectiveness. Similarly, Digital Twins and IoT technologies enable virtual environments to reflect continuously changing site conditions, supporting more responsive and data-driven safety management. Collectively, these developments indicate that VR is evolving from an immersive visualisation technology into a core component of intelligent and interconnected digital construction ecosystems.

2.3 Research Gaps and the Need for Bibliometric Analysis

The growing body of research on VR in construction safety has generated valuable knowledge regarding immersive training, hazard recognition, digital visualisation, and technology-assisted safety management. Previous review studies have synthesised many of these developments, with particular emphasis on VR-based training effectiveness, BIM-supported safety planning, and human-centred design principles. Although these reviews have contributed significantly to understanding individual applications of VR, they have primarily relied on qualitative or narrative synthesis, offering only limited insight into the overall development of the research field. As the volume of publications continues to increase, understanding the evolution of this research domain requires more than a descriptive review of existing studies. Important questions remain regarding how research topics have changed over time, which authors and institutions have played leading roles, how international collaboration networks have developed, and which emerging themes are shaping future research. Without a comprehensive quantitative assessment, it is difficult to identify the intellectual structure of the field or evaluate its long-term research trajectory. Bibliometric analysis provides an effective approach for addressing these limitations by systematically examining publication performance, citation relationships, collaboration networks, keyword co-occurrence, and thematic evolution. Rather than focusing solely on the findings of individual studies, this approach reveals broader research patterns and uncovers connections that are often overlooked in conventional review methods. Accordingly, the present study applies bibliometric techniques to provide a comprehensive overview of VR research in construction safety management between 2000 and 2024. The findings are expected to support researchers in identifying emerging research opportunities, assist practitioners in understanding technological developments, and provide evidence-based insights that can inform future research and practical implementation of immersive safety technologies.

3 Methodology

3.1 Research Design

This study adopts a bibliometric research design to systematically investigate the development of VR research in construction safety management. Bibliometric analysis provides a quantitative approach for examining the

evolution of scientific knowledge by evaluating publication performance, citation relationships, collaboration networks, and thematic structures within a research domain. Compared with conventional narrative reviews, bibliometric methods offer a more objective and reproducible assessment of research trends while revealing the intellectual structure of a scientific field (Aria & Cuccurullo, 2017). To achieve the objectives of this study, the research methodology was organised into three sequential stages. The first stage involved retrieving and preparing the bibliographic dataset from the Scopus database. The second stage focused on quantitative bibliometric analyses using Bibliometric (R package) and VOS viewer to examine publication characteristics, collaboration patterns, citation structures, and keyword relationships. The final stage consisted of interpreting and visualising the analytical results to identify major research themes, influential contributors, and emerging directions in VR-based construction safety research.

3.2 Data Collection and Screening Procedure

The bibliographic dataset used in this study was retrieved exclusively from the Scopus database because of its broad coverage of high-quality peer-reviewed publications across engineering, construction management, computer science, and occupational safety disciplines. Scopus is widely recognised as one of the most comprehensive and reliable databases for bibliometric research, providing standardised bibliographic information suitable for large-scale quantitative analyses. The literature search was conducted on 15 January 2025 using the following search query:

TITLE-ABS-KEY (“virtual reality” AND “construction safety”)

The search covered publications published between 2000 and 2024. To ensure the quality and relevance of the dataset, only peer-reviewed journal articles, review papers, and conference papers written in English were considered. Editorials, notes, book chapters, errata, duplicate records, and publications lacking sufficient bibliographic information were excluded from the analysis. The search and screening procedures resulted in a final dataset of 432 publications. Each record was manually examined based on its title, abstract, and author keywords to confirm its relevance to Virtual Reality applications in construction safety management. This manual verification helped eliminate studies outside the scope of the research while improving the reliability of the final dataset. For each selected publication, bibliographic information including authors, affiliations, publication year, source title, abstract, author keywords, country of origin, and citation data was exported in CSV format. These data served as the basis for subsequent analyses using the Bibliometrix package in R and VOS viewer.

3.3 Inclusion and Exclusion Criteria

Table 1. Inclusion and exclusion criteria used for dataset screening

Inclusion Criteria	Exclusion Criteria
Publications related to virtual reality applications in construction safety	Publications unrelated to construction safety
Peer-reviewed journal articles	Editorials, notes, errata, and book reviews
Review papers	Book chapters
Conference papers	Non-English publications
Publications between 2000 and 2024	Duplicate records
Documents indexed in Scopus	Records with incomplete bibliographic information

3.4 Tools and Analytical Procedures

The bibliometric analyses were performed using two complementary software tools: Bibliometric (R package) and VOS viewer (version 1.6.19). These tools were selected because they provide robust and widely accepted analytical capabilities for evaluating scientific literature from different perspectives. While Bibliometric supports comprehensive statistical analysis of bibliographic data, VOS viewer offers advanced network visualisation techniques that facilitate the exploration of relationships among authors, institutions, countries, publications, and research topics. The analytical workflow followed the framework proposed by Aria and Cuccurullo (2017). First, the bibliographic records exported from Scopus were imported into the Bibliometric package in R Studio, where the dataset was inspected, standardised, and prepared for analysis. Descriptive bibliometric indicators, including annual scientific production, citation performance, source productivity, and authorship characteristics, were subsequently generated to provide an overall overview of the research field. To investigate the intellectual and collaborative structure of the literature, several network analyses were conducted. Co-authorship analysis was performed to examine collaboration patterns among researchers and countries, while keyword co-occurrence analysis was used to identify dominant research themes and emerging topics within VR-based construction safety research. Citation-based analyses further supported the identification of influential publications and the evolution of scientific knowledge across the study period. Network visualisation was carried out using VOS viewer (version 1.6.19). Author keywords were selected as the unit of analysis for the keyword co-occurrence network, and a minimum occurrence threshold of five was applied to ensure that only representative research themes were included. Full counting was adopted for both keyword and co-authorship analyses to preserve all observed relationships among bibliographic items. Network, overlay, and density visualisation techniques were subsequently employed to illustrate collaboration structures, thematic clusters, and the temporal evolution of research topics. The combination of Bibliometric and VOS viewer enabled both quantitative performance analysis and science mapping, providing a comprehensive understanding of publication trends, collaboration patterns, thematic development, and the intellectual structure of VR research in construction safety management.

3.5 Limitations of the Methodology

While bibliometric analysis provides valuable quantitative insights, certain limitations must be acknowledged. The study's reliance on a single database (Scopus) may exclude relevant works indexed elsewhere, such as Web of Science or Google Scholar. Additionally, citation counts may not fully reflect the academic impact or practical relevance of a publication. Finally, the interpretation of keyword clusters involves some level of subjectivity, despite being based on quantitative data. Nevertheless, bibliometric methods offer a robust foundation for understanding research landscapes and identifying emerging themes, especially when combined with visualisation tools and trend analyses. Although integrating multiple databases such as Web of Science may increase coverage, Scopus was selected as the primary source because of its broader journal coverage in engineering, construction management, and technology-related disciplines. Previous bibliometric studies have demonstrated that Scopus provides sufficient coverage for identifying major research trends and influential publications within the construction management domain (Aria & Cuccurullo, 2017). The findings obtained through these analytical procedures are presented and discussed in the following section.

4 Results and Analysis

4.1 Overview of Publication Trends

A total of 432 publications related to the application of VR in construction safety management were identified and analysed for the period between 2000 and 2024. The publication trend illustrates the progressive development of this research field from a relatively niche topic into one of the most active areas within digital construction safety. During the early years (2000–2010), research activity remained limited and primarily focused on exploring the feasibility of VR technologies for construction education, safety visualisation, and basic training applications. The relatively small number of publications during this period reflects both the

technological limitations of early VR systems and the restricted accessibility of immersive hardware. A noticeable increase in research productivity emerged after 2015, corresponding with significant advances in VR hardware, software platforms, and their integration with digital construction technologies such as BIM. This period marks the transition of VR from an experimental visualisation tool to a practical technology capable of supporting hazard recognition, safety training, and decision-making in construction environments. As illustrated in Figure 1, annual scientific production accelerated substantially after 2018, with publication output increasing rapidly and reaching its highest level in 2022. This growth reflects the expanding academic and industrial interest in immersive technologies as practical solutions for improving construction safety performance. The figure also indicates that the research field has maintained consistent momentum in recent years rather than experiencing temporary fluctuations, suggesting that VR has become an established research direction within construction safety management. Although publication output has increased considerably, citation patterns indicate that a relatively small group of pioneering studies published between 2008 and 2015 continues to exert substantial influence on subsequent research. This observation suggests that while the field is expanding rapidly, its intellectual foundation remains anchored in several highly influential contributions that continue to shape contemporary research themes, technological developments, and methodological approaches.

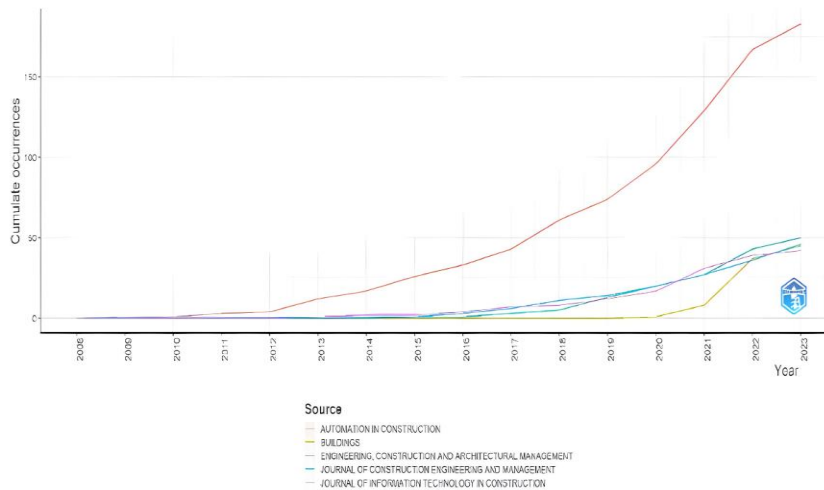


Figure 1. Source production over time

Table 2. Most productive sources

Journal	Publications
Automation in Construction	183
Engineering, Construction and Architectural Management	50
Journal of Construction Engineering and Management	46
Buildings	45
Journal of Information Technology in Construction	42
Safety Science	37
Construction Innovation	35
Applied Sciences	33

Journal	Publications
Smart and Sustainable Built Environment	24
Journal of Computing in Civil Engineering	21

Table 2 summarises the journals that have contributed most extensively to the development of VR research in construction safety management. The distribution of publications demonstrates that research output is concentrated within a relatively small group of specialised journals focusing on construction engineering, digital technologies, and occupational safety. Automation in Construction clearly dominates the field, highlighting its central role in disseminating innovative research on digital transformation and immersive technologies in construction. The strong representation of journals such as Engineering, Construction and Architectural Management, Journal of Construction Engineering and Management, and Safety Science further indicates that VR research has evolved as an interdisciplinary topic that integrates engineering, construction management, and safety science. This concentration of publications also suggests that future advances in VR-based construction safety are likely to continue emerging from these leading publication outlets.

4.2 Most Influential Authors, Institutions, and Countries

The bibliometric analysis identified a diverse and internationally distributed research community comprising 265 authors from 37 countries. Despite this geographical diversity, scientific productivity and citation impact are concentrated among a relatively small number of influential researchers who have played a pivotal role in advancing VR applications for construction safety. Their contributions extend beyond publication output by establishing the theoretical foundations, methodological approaches, and technological innovations that continue to influence contemporary research. As summarised in Table 3, authors such as Wang X., Li H., Du J., Gheisari M., Teizer J., and Arashpour M. have consistently contributed to the development of VR-based safety research through studies on immersive training, BIM integration, digital construction, safety monitoring, and human-centred technologies. Their high citation counts indicate that these researchers have not only produced a substantial body of work but have also significantly shaped subsequent investigations in the field. Institutional productivity exhibits a similar pattern. Universities including The Hong Kong Polytechnic University, Tsinghua University, the National University of Singapore, and the University of New South Wales emerge as major research centres, reflecting sustained investment in digital construction technologies and occupational safety research. The prominence of these institutions demonstrates the important role of interdisciplinary collaboration among engineering, computer science, and construction management researchers. At the national level, China, the United States, and the United Kingdom account for the largest share of scientific output and citation impact. This leadership reflects strong national research investments in digital construction and the widespread adoption of emerging technologies within the construction sector. Furthermore, the collaboration network indicates that international partnerships—particularly between China and the United States—have become increasingly influential in accelerating knowledge exchange and promoting the global development of VR-based construction safety research.

Table 3. Leading authors and their research contributions in VR-based construction safety

Author	Publications	Total Citations	Main Research Focus
Li H.	25	973	BIM–VR integration and construction safety
Du J.	24	718	Immersive technologies and safety training
Gheisari M.	23	400	Human factors and VR applications
Teizer J.	16	1439	Construction safety monitoring and digital technologies

Author	Publications	Total Citations	Main Research Focus
Wang X.	26	2449	Digital construction and VR-enabled safety systems
Arashpour M.	14	523	Construction innovation and digitalisation

The concentration of influential authors within a relatively limited group suggests that knowledge development in this research field has been driven by several well-established research teams. At the same time, the growing diversity of contributing countries and institutions indicates that VR-based construction safety has evolved into an increasingly international research domain. This balance between established leadership and expanding global participation reflects the maturation of the field and provides opportunities for broader interdisciplinary collaboration in future studies. Overall, Table 3 demonstrates that research productivity is concentrated among a relatively small group of highly influential authors, indicating the existence of several leading research hubs within the field.

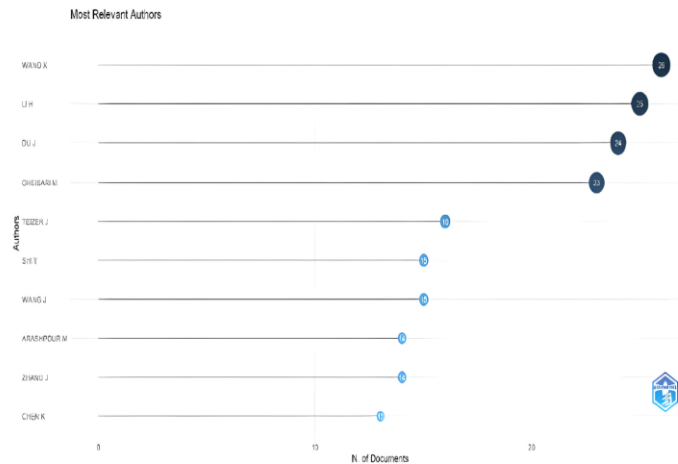


Figure 2. Most relevant sources

Table 4. Major research clusters identified through keyword co-occurrence analysis

Cluster	Dominant Keywords	Interpretation
Cluster 1	Virtual Training, Hazard Recognition, Safety Learning	Focus on immersive safety education and worker training
Cluster 2	BIM, Digital Twin, Simulation	Integration of VR with digital construction technologies
Cluster 3	Human–Computer Interaction, Cognitive Load, Ergonomics	User experience and behavioural safety
Cluster 4	Artificial Intelligence, Machine Learning, IoT	Intelligent and predictive safety systems

Table 4 complements the network visualisation by summarising the dominant research themes represented within each cluster. Together, Figure 3 and Table 4 demonstrate that the evolution of VR research has not occurred through isolated technological advances but through the gradual convergence of immersive visualisation, digital construction technologies, human-centred design, and intelligent data-driven safety management. This thematic diversity reflects the increasing maturity of the research field and highlights several promising directions for future investigation.

4.3 Source Impact and Journal Distribution

The bibliometric analysis identified that the majority of publications were concentrated in a limited number of high-impact journals. Automation in Construction, Journal of Construction Engineering and Management (JCEM), and Safety Science collectively account for a considerable share of the indexed publications. These journals serve as primary outlets for research that bridges technological innovation with safety practices. The high citation counts observed in these outlets confirm their critical role in shaping the theoretical and methodological foundation of VR applications in safety management.

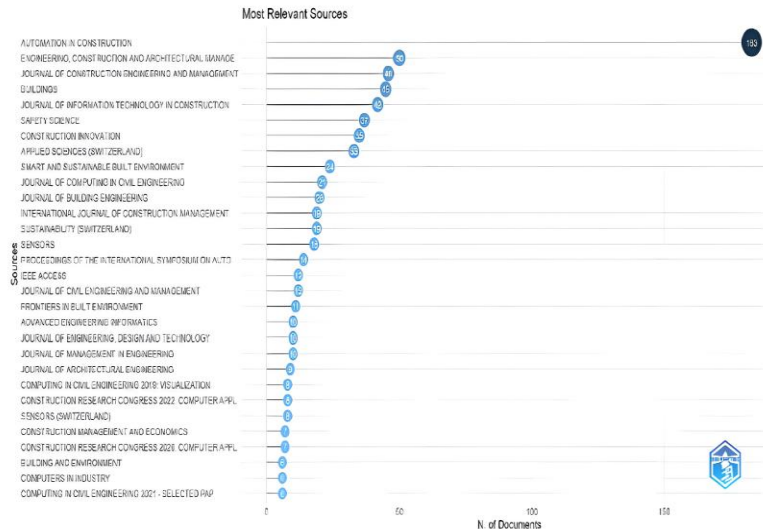


Figure 3. Most relevant authors

4.4 Keyword Co-Occurrence and Thematic Clusters

Keyword co-occurrence analysis was conducted to identify the principal research themes and reveal the intellectual structure of VR research in construction safety management. By examining the frequency with which author keywords appear together, this analysis provides insight into the conceptual organisation of the research field and highlights the relationships among its major topics. The resulting network, generated using VOS viewer, is presented in Figure 3. Figure 3 illustrates four major thematic clusters that collectively represent the evolution and current research priorities of VR applications in construction safety. Rather than existing as isolated research areas, these clusters demonstrate strong conceptual connections, reflecting the multidisciplinary nature of digital construction safety research. The network structure indicates that VR serves as a central platform linking technological innovation, human factors, digital engineering, and intelligent safety management.

The first cluster focuses on VR-based safety training and education. Keywords such as virtual training, hazard recognition, and safety learning dominate this group, emphasising the widespread use of immersive environments to improve workers' hazard awareness, practical decision-making, and knowledge retention. The strong interconnections among these keywords indicate that educational applications remain the fundamental research direction within the field. The second cluster represents the integration of VR with digital construction technologies. The close association among BIM, Digital Twin, and simulation reflects the increasing adoption of integrated digital platforms for safety planning, risk visualisation, and project management. The emergence of this cluster demonstrates the transition from stand-alone VR applications toward comprehensive digital construction ecosystems. The third cluster highlights research on human factors and behavioural safety. Frequently occurring keywords such as human–computer interaction, cognitive load, and ergonomics indicate growing attention to the psychological and physiological dimensions of immersive learning. Rather than focusing solely on technological performance, recent studies increasingly evaluate how users interact with VR environments and how these interactions influence learning effectiveness, safety behaviour, and decision-making. Recent meta-analytic evidence further confirms that immersive VR training significantly improves knowledge acquisition, hazard recognition, and safety performance among construction workers (Man et al., 2024). The fourth cluster reflects the emergence of intelligent safety management systems through the integration of Artificial Intelligence, Machine Learning, and the Internet of Things. Compared with the other clusters, this group represents one of the newest research directions, illustrating how immersive technologies are evolving toward adaptive, predictive, and data-driven safety management solutions capable of responding dynamically to changing construction environments. Overall, the keyword network demonstrates that research on VR in construction safety has progressed from technology-oriented visualisation toward integrated, intelligent, and human-centred safety systems. The close relationships among the four clusters further suggest that future developments will increasingly depend on interdisciplinary collaboration across digital construction, artificial intelligence, occupational safety, and human-centred design.

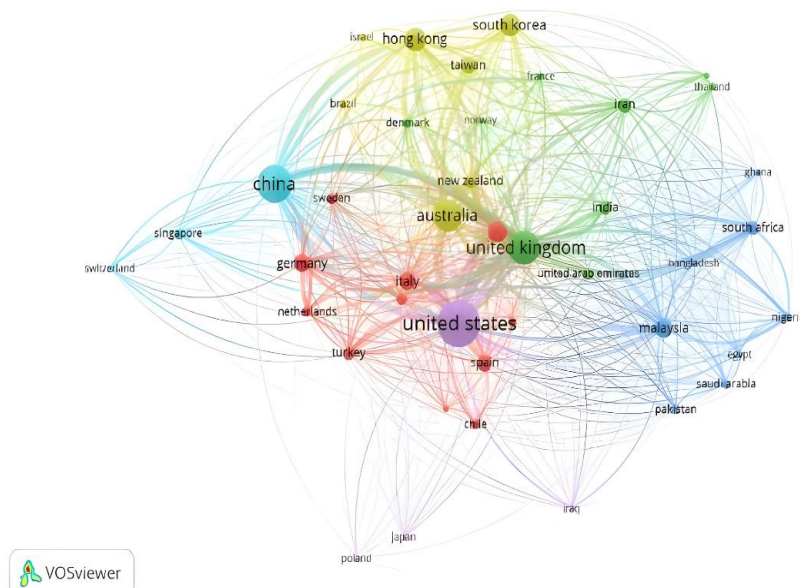


Figure 4. Most collaborating countries

Table 5. Leading countries in VR construction safety research

Country	Publications*
United States	304
China	197

Country	Publications*
United Kingdom	152
Australia	134
Hong Kong	75
South Korea	70
Canada	60
Malaysia	53
Germany	47
Italy	43

Table 6. Major relationships identified in the three-field plot

Country	Influential Authors	Dominant Research Topics
United States	Wang X., Teizer J., Gheisari M.	Virtual Reality, Construction Safety, BIM
China	Li H., Du J., Zhang J.	Safety Training, Hazard Recognition, BIM
Australia	Arashpour M., Edwards D.	Digital Construction, Immersive Learning
United Kingdom	Hosseini M.R., Man S.	BIM Integration and Safety Management
Hong Kong	Li H., Lu Y.	VR-based Safety Training

Table 6 further summarises the principal relationships identified in the three-field plot. The distribution of authors and research topics demonstrates that influential researchers are closely associated with specific thematic domains, reflecting the gradual specialisation of the field. At the same time, the presence of similar research topics across multiple countries suggests that international collaboration has contributed to the global diffusion of knowledge and accelerated the development of VR-enabled safety research.

collaborative relationships have become progressively stronger over time, reflecting the growing internationalisation of research activities in this field. While early studies were primarily conducted within individual institutions or national research groups, recent years have witnessed a substantial increase in multi-institutional and multinational collaborations. The collaboration network reveals particularly strong partnerships among researchers from China, the United States, the United Kingdom, Australia, Singapore, and South Korea. These collaborative relationships indicate that the advancement of VR-based construction safety research increasingly depends on the integration of expertise from construction engineering, computer science, occupational safety, and digital technologies. Such interdisciplinary cooperation has accelerated both methodological innovation and the practical implementation of immersive technologies within the construction industry. Beyond illustrating research partnerships, the collaboration network demonstrates the growing globalisation of scientific knowledge. Countries with extensive international collaborations generally exhibit higher publication productivity and greater thematic diversity, suggesting that collaborative research environments promote broader exploration of emerging technologies and facilitate the dissemination of innovative safety practices across different regions. The thematic evolution analysis further illustrates how the research field has progressed over the past two decades. During the initial exploration phase (2000–2010), studies focused primarily on evaluating the technical feasibility of VR systems and their potential applications in construction safety education. Research at this stage was largely technology-driven, with emphasis placed on visualisation capabilities and prototype development. Between 2011 and 2017, research entered a development phase characterised by increasing realism, improved simulation environments, and the integration of BIM into VR applications. During this period, researchers shifted their attention from technological feasibility toward practical implementation, emphasising hazard identification, safety planning, and interactive learning environments. The most recent period (2018–2024) represents a phase of rapid expansion and technological convergence. Research has increasingly incorporated AI, Digital Twins, IoT technologies, advanced sensing systems, and human-centred design principles to develop adaptive and intelligent safety management solutions. Rather than functioning solely as an immersive visualisation tool, VR has become an essential component of integrated digital construction ecosystems capable of supporting predictive safety management and evidence-based decision-making. Overall, the collaboration and thematic evolution analyses indicate that VR research in construction safety has matured into an interdisciplinary and internationally connected research domain. The continuous expansion of collaborative networks, together with the emergence of intelligent digital technologies, suggests that future research will increasingly focus on integrated, data-driven, and adaptive approaches to improving construction safety performance.

5 Discussion

The findings of this bibliometric analysis demonstrate that research on VR in construction safety has experienced remarkable growth over the past two decades, reflecting the broader digital transformation of the construction industry. Rather than representing a temporary technological trend, the continuous increase in publication output suggests that VR has become an established research domain with expanding theoretical, methodological, and practical significance. This growth has been driven by rapid advances in immersive technologies, decreasing hardware costs, and the increasing demand for innovative approaches to improving occupational safety in complex construction environments. The publication trends identified in this study are consistent with previous review studies reporting a growing interest in immersive technologies for construction safety training and risk management. However, unlike earlier narrative and systematic reviews, the present bibliometric analysis provides quantitative evidence of how the research field has evolved, identifying not only the increase in scientific production but also the structural relationships among authors, countries, institutions, and research themes. This broader perspective contributes to a more comprehensive understanding of the intellectual development of the field. One of the most important observations emerging from this study is the gradual shift in research priorities. Early investigations primarily focused on demonstrating the technical feasibility of VR systems and evaluating their potential for visualisation and safety education. As immersive technologies matured, research progressively expanded toward integrating VR with BIM, Digital Twins, Artificial Intelligence, and Internet of Things technologies. This transition indicates that VR is no longer viewed as an isolated visualisation tool but rather as an integral component of intelligent and data-driven construction

safety management systems. The thematic evolution identified through keyword co-occurrence analysis further supports this transformation. The coexistence of themes related to immersive learning, digital construction, human factors, and intelligent technologies suggests that future research will increasingly rely on interdisciplinary collaboration. Consequently, the development of VR-based construction safety is expected to depend not only on technological innovation but also on advances in cognitive science, human–computer interaction, artificial intelligence, and digital engineering.

5.1 Human Factors and Emerging Intelligent Technologies

One of the most significant findings of this study is the gradual shift from technology-oriented research toward human-centred and intelligent safety management approaches. The keyword co-occurrence analysis indicates that, although early studies primarily emphasised VR hardware capabilities and visualisation techniques, recent research increasingly focuses on understanding how users interact with immersive environments and how these interactions influence safety-related behaviour, learning effectiveness, and decision-making. The growing prominence of keywords associated with human–computer interaction, cognitive load, ergonomics, and behavioural safety reflect an important change in research priorities. Rather than evaluating VR systems solely based on their technical performance, contemporary studies recognise that the effectiveness of immersive safety training depends largely on user experience, cognitive engagement, and the ability of virtual environments to simulate realistic construction scenarios. These findings are consistent with previous research emphasising the importance of human-centred design principles in improving learning outcomes and reducing human error during safety training. Another notable development revealed by the bibliometric analysis is the rapid emergence of AI, Digital Twins, and IoT technologies within the VR research landscape. The increasing integration of these technologies demonstrates that immersive environments are evolving beyond visualisation platforms into intelligent decision-support systems capable of adaptive learning, predictive risk assessment, and real-time safety monitoring. The convergence of VR with AI and digital construction technologies also reflects the broader digital transformation occurring across the construction industry. Intelligent VR systems have the potential to personalise safety training, analyse user behaviour, and dynamically modify training scenarios according to individual performance. Consequently, future research is likely to move beyond the development of immersive environments toward the creation of integrated digital ecosystems that combine sensing technologies, artificial intelligence, and human-centred design to enhance construction safety performance.

5.2 International Collaboration and Research Implications

The collaboration networks identified in this study demonstrate that the advancement of VR research in construction safety increasingly depends on international and interdisciplinary cooperation. The strong collaborative links observed among China, the United States, the United Kingdom, Australia, Singapore, and several other countries indicate that knowledge development is no longer confined to individual institutions or national research communities. Instead, scientific progress is being driven by the exchange of expertise across construction engineering, computer science, occupational safety, and digital technologies. This increasing level of international collaboration has important implications for both research quality and technological innovation. Collaborative research environments facilitate the sharing of datasets, software tools, experimental platforms, and practical experiences, enabling researchers to develop more comprehensive and robust VR applications. Such partnerships also accelerate the translation of academic research into practical solutions capable of addressing real-world safety challenges within increasingly complex construction projects. From a theoretical perspective, the findings of this bibliometric analysis demonstrate that VR research has evolved into a multidisciplinary knowledge domain that integrates concepts from construction management, human–computer interaction, artificial intelligence, and digital engineering. The identified thematic clusters and collaboration patterns contribute to a clearer understanding of how scientific knowledge has developed over time and provide a structured framework for future bibliometric investigations. From a practical perspective, the results highlight the growing importance of immersive technologies for improving safety training, hazard recognition, and decision-making within construction environments. Construction organisations may benefit from integrating VR with complementary digital technologies such as BIM, Digital Twins, AI, and IoT systems to establish more

adaptive, predictive, and data-driven safety management strategies. Such integration has the potential to reduce workplace accidents, improve training effectiveness, and support evidence-based safety planning throughout the project lifecycle. The findings also suggest several promising directions for future research. Greater attention should be devoted to evaluating the long-term effectiveness of VR-based safety training under real construction conditions, investigating user acceptance across different cultural and organisational contexts, and developing intelligent VR systems capable of adapting training scenarios according to individual performance and behavioural responses. Future studies may also benefit from integrating bibliometric techniques with systematic literature reviews or meta-analyses to obtain both quantitative and qualitative perspectives on the continuing evolution of this rapidly expanding research field. Taken together, these findings indicate that VR research has progressed beyond technological innovation toward the development of integrated, intelligent, and human-centred safety management systems capable of addressing increasingly complex construction environments.

6 Conclusion

This study presented a comprehensive bibliometric analysis of research on Virtual Reality (VR) applications in construction safety management based on 432 publications indexed in the Scopus database between 2000 and 2024. By combining quantitative bibliometric techniques with science mapping approaches, the study systematically examined publication trends, influential authors, leading institutions, international collaboration networks, and the thematic evolution of the research field. The findings demonstrate that VR research has evolved from an emerging visualisation technology into an interdisciplinary research domain that integrates Building Information Modelling (BIM), Artificial Intelligence (AI), Digital Twins, Internet of Things (IoT), and human-centred design principles to improve construction safety management. The results further reveal a continuous increase in scientific productivity, stronger international collaboration, and the emergence of new research themes emphasising intelligent, adaptive, and data-driven safety systems. Unlike previous review studies that primarily relied on qualitative synthesis, this research provides a quantitative perspective on the intellectual structure and development of the field. Through co-authorship analysis, keyword co-occurrence mapping, citation analysis, and thematic evolution assessment, the study identifies the principal contributors, dominant research themes, and emerging directions that have shaped the development of VR-based construction safety research over the past two decades. From a practical perspective, the findings highlight the growing potential of immersive technologies to improve hazard recognition, safety training, risk communication, and decision-making throughout the construction project lifecycle. The integration of VR with complementary digital technologies offers significant opportunities for developing more proactive, adaptive, and evidence-based safety management strategies capable of addressing increasingly complex construction environments. Overall, this study provides a comprehensive overview of the evolution of VR research in construction safety while offering valuable guidance for researchers, practitioners, and policymakers. The identified collaboration patterns, thematic developments, and emerging research directions may serve as a useful foundation for future scientific investigations and for the continued digital transformation of construction safety management. As immersive technologies continue to evolve, the findings of this study provide a valuable knowledge base for guiding future research and supporting the digital transformation of construction safety management worldwide.

6.1 Limitations and Future Research

Although this study provides a comprehensive bibliometric overview of Virtual Reality (VR) research in construction safety management, several limitations should be acknowledged when interpreting the findings. First, the bibliometric dataset was retrieved exclusively from the Scopus database. Although Scopus is one of the largest and most reliable bibliographic databases, relevant publications indexed in other databases such as Web of Science, Dimensions, or IEEE Xplore were not included. Consequently, some influential studies may not be fully represented in the present analysis. Second, only English-language publications were considered. Excluding studies published in other languages may have limited the geographical and cultural diversity of the dataset, particularly with respect to research conducted in regions where English is not the primary language of scientific communication. Third, bibliometric analysis primarily identifies publication patterns, collaboration networks, citation relationships, and thematic structures. While these quantitative techniques provide valuable

insights into the evolution of a research field, they do not assess the methodological quality or empirical rigour of individual studies. Therefore, the findings should be interpreted as representing the overall intellectual structure of the literature rather than the quality of specific research contributions. Future research may overcome these limitations by incorporating multiple bibliographic databases, including non-English publications, and combining bibliometric techniques with systematic literature reviews or meta-analyses. Such integrated approaches would provide both quantitative and qualitative perspectives, enabling a more comprehensive understanding of the continuing evolution of VR applications in construction safety management. These findings are consistent with recent studies suggesting that Digital Twin technologies, combined with VR, AI, and BIM, represent one of the most promising directions for the next generation of intelligent construction safety management systems (Saif et al., 2024).

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Declaration of Conflicting Interests

The author declares that there are no conflicts of interest.

Author Contribution

Conceptualisation, Mohammad Sadegh Roghanian; Methodology, Mohammad Sadegh Roghanian; Validation, Mohammad Sadegh Roghanian; Analysis, Mohammad Sadegh Roghanian; Investigation, Mohammad Sadegh Roghanian; Resources, Mohammad Sadegh Roghanian; Data Curation, Mohammad Sadegh Roghanian; Writing—Original Draft Preparation, Mohammad Sadegh Roghanian; Writing—Review & Editing, Mohammad Sadegh Roghanian; Visualisation, Mohammad Sadegh Roghanian.

Declaration of Generative AI in The Writing Process

Not Applicable.

Data Availability/Supplementary Materials

The bibliographic data used in this study were retrieved from the Scopus database. The search strategy and screening procedure are described in the manuscript. The underlying bibliographic records are available from the corresponding author on reasonable request, subject to Scopus licensing and access restrictions.

Ethics Statement

The authors declare that this research did not involve human or animal subjects.

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