“Safety management in the construction industry: Bibliometric analysis”

AUTHORS	Khanlar Ganiyev Shahla Alizada Anar Asgarov Murad Gasimli Nail Gasimzade

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Khanlar Ganiyev (Azerbaijan), **Shahla Alizada** (Azerbaijan), **Anar Asgarov** (Azerbaijan), **Murad Gasimli** (Azerbaijan), **Nail Gasimzade** (Azerbaijan)

SAFETY MANAGEMENT IN THE CONSTRUCTION INDUSTRY: BIBLIOMETRIC ANALYSIS

Abstract

Despite the continuous improvement of safety standards in the construction industry, this sphere remains one of the most hazardous sectors, and safety management is becoming a crucial determinant of effective operation at construction sites. The aim of this study is to identify the essential contextual, evolutionary-chronological, and geographical-industrial scientific landscape of the development of safety management in the construction industry through comprehensive bibliometric analysis. More than 15,000 articles indexed by Scopus from around the world from 2000 to 2023 were analyzed using the VOSviewer tool, filtered by keywords such as "construction," "safety," and "management." The research revealed the intensification of publishing activity since 2012 (with peak growth in 2012, 2020, and 2022). The leading scientists are from China, the United States, and the United Kingdom (e.g., Chinese scientists make up 26.1% of all scholars). The majority of papers are in the field of engineering. Priority areas of research include safety climate, safety behavior, and building information modeling. The closest connections of construction safety management are with the study of professional risks, safety techniques, and quality control. The evolution of research focuses on "human health and safety-risks-digital security systems." In general, the findings of this study provide a foundation for future research aimed at enhancing safety management in the construction field, potentially increasing worker protection and technical operational efficiency.

Keywords safety regulations, risk management, workplace incidents, safety standards, construction hazard, ISO, safety protocols

JEL Classification L74, J53, N60

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Khanlar Ganiyev, Ph.D. in Economics, Senior Lecturer, Department of Business Economics and Management, Azerbaijan University of Architecture and Construction, Azerbaijan. (Corresponding author)

Shahla Alizada, Ph.D. in Economics, Senior Lecturer, Department of Business Economics and Management, Azerbaijan University of Architecture and Construction, Azerbaijan.

Anar Asgarov, Postgraduate Student, Department of Business Economics and Management, Azerbaijan University of Architecture and Construction, Azerbaijan.

Murad Gasimli, Postgraduate Student, Department of Business Economics and Management, Azerbaijan University of Architecture and Construction, Azerbaijan.

Nail Gasimzade, Postgraduate Student, Department of Business Economics and Management, Azerbaijan University of Architecture and Construction, Azerbaijan.

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INTRODUCTION

Safety management in the construction industry is essential, as this industry remains one of the most dangerous sectors with various occupational risks on construction sites, where numerous accidents and fatalities occur annually (Luo et al., 2022). A significant number of absences among full-time construction workers are annually recorded due to injury or illness, totaling 24.2 million. This underscores the substantial impact of occupational hazards in the workplace. Statistically, based on the United States example, incidents related to construction accidents rose during 2022, with 1,056 reported incidents, marking an 11% increase from the previous year. Falls, slips, or trips accounted for a significant portion, resulting in 423 fatalities, emphasizing the heightened vulnerability of workers to accidents on construction sites. The fatality rate within the construction sector serves as a stark indicator of the inherent dangers associated with such work. In the US, the fatality rate was 12.3 per 100,000 full-time workers in 2021, highlighting the persistent occupational risks faced by the workforce. This rate increased to 13 accidents per 100,000 full-time workers in 2022, indicating a concerning trend marked by increased risk exposure and escalating safety concerns. Furthermore, there are substantial risks,

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such as natural hazards, leading to significant damages. For example, in 2022, the cost of damages from storms amounted to 131 billion U.S. dollars, while floods caused 44.9 billion U.S. dollars in damages, and droughts and earthquakes caused billions of U.S. dollars in damages (Dyvik, 2024).

The International Labour Organization (ILO) plays a pivotal role in supporting safety management initiatives through the periodic development and revision of the Safety and Health in Construction Code of Practice, the most recent update of which occurred in February 2024. Moreover, the construction industry encompasses a diverse array of stakeholders, including contractors, subcontractors, architects, engineers, suppliers, and other professionals, all operating within a regulatory framework established by the International Organization for Standardization (ISO), a global entity responsible for setting international standards. Particularly noteworthy within this framework is ISO 9001, serving as the principal standard for quality management systems, while ISO 45001 supersedes the former OHSAS 18001 system as the internationally recognized standard for health and safety management. ISO 22014:2024 specifically addresses the unique requirements of the architecture, engineering, and construction sectors. Furthermore, the World Bank has developed Environmental, Health, and Safety (EHS) Guidelines, which furnish practical exemplars of exemplary industry practices, including those pertinent to construction. These guidelines are meticulously tailored to account for project-specific hazards and risks, with due consideration given to environmental factors and project characteristics. Additionally, the regulatory landscape is further augmented by national standards and regulations promulgated by governmental authorities, informed by a spectrum of factors encompassing ecological, economic, social, and other considerations.

That is why, with the diversity of safety management in the construction industry, it is reasonable to explore the specific areas to investigate which aspects of safety management are at the forefront of scientific interest. Research in this domain can unveil the primary factors contributing to accidents and injuries at construction sites and devise effective strategies for their management. Studying safety management in the construction industry can encompass a wide range of aspects, including the integration of cutting-edge technologies into construction processes, enhancing the professional skills of workers, and developing organizational and control mechanisms to prevent and mitigate risks. Such research holds significant potential for improving safety on construction sites, leading to a reduction in accidents and injuries among the workforce in this industry.

1. LITERATURE REVIEW

Safety management in the construction industry has garnered significant academic interest due to its impact on all spheres of life, driven by globalization, technological change, and social aspects. Safety is ensured by quality of life, such as management, by covering various aspects of addressing essential fundamentals before issues (Mullens & Shen, 2023; Zámek & Zakharkina, 2024). Therefore, safety management systems share foundational similarities across contexts but are adapted to unique structures (Jazayeri & Dadi, 2017).

The foundational principles of safety management encompass critical elements, such as risk assessment, prevention, regulatory compliance, training programs, and fostering a robust safety culture (Filemon et al., 2024). Analyzing data factors can identify predictors of risk levels on construction sites, including complexity and resource factors (Forteza et al., 2017). Design for Safety (DFS) is pivotal in safety management, advocating proactive risk prevention through integrated safety design and leveraging quality methodologies and technologies (Zhu et al., 2023; Aid et al., 2024). Therefore, it is beneficial to utilize multiple sources of evidence to adopt best practices in safety management in construction. A notable example of this is Brazil (Bridi et al., 2021). Additionally, various behavioral models regarding safety strategies impact risk management. Risk assessment employs diverse methods while adhering to legislative requirements, with safety experts responsible for conducting risk assessments and transferring knowledge to managers and workers involved

in construction safety provision and organization (Gunduz, 2018). Identifying trends in deep learning for safety analysis in construction and other technical aspects underscores the evolving landscape of risk modeling and safety management, emphasizing practicality and efficiency in construction (Akinosho et al., 2020). This could be based on international ISO standards certification (Choe, 2017; Gunduz, 2018) to develop risk models and calls for further refinement, particularly in safety-related approaches (Jazayeri & Dadi, 2017). Furthermore, effective risk management and value engineering in construction are crucial for reducing overall project costs and maintaining its value and quality through technology (Choe, 2017). Additionally, the impact of transparent accounting information on construction investments, the number of construction firms, annual construction work volumes, and total employees in construction firms is significant (Abbasova et al., 2022; Pozdnyakov et al., 2022; Brychko et al., 2023).

To effectively prevent any kind of risks, including safety risks, on the construction side, strategies include local protocols, employee training, and rigorous safety procedures (Gunduz, 2018). For instance, improving workplace safety for construction workers and enhancing employee satisfaction levels are crucial. This comprehensive approach allows for detailed analysis of factors contributing to accidents, facilitating targeted measures for risk reduction (Kuzior et al., 2022a). Managing construction processes involves mitigating risks such as cost escalations, limited credit access, and labor shortages, optimizing risk management strategies through leadership that impacts productivity (Alkaissy et al., 2020; Gentsoudi, 2023), and meeting stringent safety standards and addressing adverse weather conditions (International Labour Organization, 2023).

Safety management practices have evolved over time within the construction industry, encompassing historical developments, changes in regulations, advancements in safety equipment and technology, and improvements in safety standards (Mujtaba & Kaifi, 2023). Initially, government interventions have been pivotal in shaping management authority in the construction industry, influencing financial regulations and security (Prokopenko et al., 2023; Pshyk et al., 2022), and fostering investments in housing construction to stimulate economic growth. Moreover, regulatory compliance and skill requirements become crucial in Brazil, China, South Africa, and Malaysia (Umeokafor et al., 2022). Public health management is a part of safety management, including the promotion of affordable mortgage lending to alleviate overcrowding and enhance population well-being. Furthermore, quality management practices influence construction project effectiveness (Guo et al., 2017). Moderated by project management in contemporary construction projects, along with managing intricate financial movements (Njegovanovic, 2023; Njegovanovic, 2024; Kuzior et al., 2023; Ololade et al., 2023), it makes significant contributions.

Government and government authorities ensure economic and social sustainability by ensuring access to safe and affordable construction (Tahat, 2023; Bhandari, 2023; Springs, 2024). They confront global crises, such as social crises (Kaya & Engkuchik, 2024), and ensure national security (Didenko et al., 2020). These crises include social crises like the unpreparedness of management for COVID-19 (Al-Hashimi et al., 2023; Richardson, 2024), financial crises (Banerjee et al., 2023; Bensadok & Abid, 2023; Douha et al., 2022; Kerimov et al., 2023), and environmental crises (Didenko et al., 2021). To address these crises, there are trends in organizational development (Skrynnyk, 2023) and the adoption of artificial intelligence technologies in management. For instance, the development of macro-level management approaches introduces unique perspectives, such as Sharing Economy Business Models (SEBMs) (Zhghenti, 2023). These are significant components of contemporary social and economic growth.

Key performance indicators such as safety, quality, productivity, and cost are critical in construction (Koibichuk et al., 2023). Prioritizing these ensures safety for stakeholders and minimizes risks. There is a significant correlation between construction safety management strategies and quality management (Wanberg et al., 2013). Construction projects often employ multinational workforces, as seen in the United Kingdom, including migrant workers, which can lead to compliance challenges with laws and standards influenced by national

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cultures, affecting work practices for workers and supervisors. Issues related to poor worker welfare may arise (Oswald et al., 2018). Enhancing working conditions and health in the construction industry is pivotal for safety improvement. Focusing on workers' health and workplace conditions directly correlates with reducing accidents and enhancing productivity, exemplified by the decline in accidents in the US construction industry after the enactment of labor protection laws in 1970 (Wetzel & Thabet, 2015). However, injury rates positively correlate with rework, demolition, schedule pressures, and unstable work processes (Loosemore & Malouf, 2019), along with inadequate provision of personal protection equipment, safety meetings, and training (Tam et al., 2014). Developing effective safety strategies involves proactive planning, time allocation, on-site leadership, and fostering pride in workmanship and safety compliance among employees. Safety management in construction includes standards, guidelines, and collaborative tools for identifying and mitigating hazards (International Labour Organization, 2022). Effective safety management integrates strategies that consider safety, quality, productivity, and cost. Training initiatives and improved working conditions are crucial for cultivating positive safety attitudes. Methods like risk assessment and technological advancements further enhance safety practices.

The significance of Safety Management Systems (SMS) in mitigating accidents is underscored (Otitolaiye & Abd Aziz, 2024), as elucidated in an analysis of construction health and safety literature disseminated in the 21st century via the Elsevier Scopus platform. This analysis focused on various aspects, including construction safety in both developed and developing nations, primary organizations engaged in construction safety research, key authors and research domains, as well as emerging research directions in construction safety. For instance, in the Australian construction sector, a shift toward viewing safety not merely as a concern resulted in improved safety knowledge post-training, although demographics such as gender, age, and education influence the formation of safety attitudes (Loosemore & Malouf, 2019).

In the literature landscape of safety management on construction sites, there is a gap in knowledge, such as design for security and digital technology integration based on data from the Web of Science (WoS). Modern safety management aligns with current trends, such as the use of smart, green, and sustainable building materials (Rajendra & Mohanasundaram, 2023; Kuzior et al., 2022b) and the utilization of green technologies and artificial neural networks (Kristanti et al., 2023). Reliable supply chain management mechanisms (Doroshenko et al., 2023; Tahat, 2023) and improved risk identification through visualization techniques, integrating building information modeling, location tracking, and augmented reality highlight their potential for enhancing worker awareness and facilitating effective communication between management and workers on construction sites (Park et al., 2015). Technical advancements integrating data from both Web of Science (WoS) and Scopus (Dobrucali et al., 2023) reveal divergent technology adoption trends across geographical contexts. In addition, sensors and wireless technologies emerge as pivotal components of construction safety, with artificial intelligence, machine learning, and building information modeling (BIM) gaining traction as leading-edge technologies. In contrast, technologies like drones, gamification, and the Internet of Things (IoT) are comparatively less prevalent. Current research aims to enhance construction site health and safety through technologies such as virtual reality (VR), online databases, Geographic Information Systems (GIS), Building Information Modeling (BIM), Unmanned Aerial Vehicles (UAVs), and 4D Computer-Aided Design (CAD) (Akinlolu et al., 2020).

Therefore, this study aims to investigate content-contextual, evolutionary-temporal, and spatial regularities using complex bibliometric analysis regarding the global scientific landscape of the development of safety management in the construction industry worldwide.

2. METHODOLOGY

The study design is structured around a series of inquiries aimed at appropriate bibliometric methods that can in field of safety management in the construction industry.

First (Study design), the methodology entails the examination of the research field's structure, fo-

cusing on identifying the key directions and theoretical frameworks, exploratory the conceptual structure of the research field, and producing a geographical and social network structure.

Second (Sample/Data collection), the sample of documents was downloaded from Scopus in February 2024. Scopus databases were selected as tools for tracking and analyzing trends in academic research, assumed by their reliable repositories of scholarly works and citations, allowing for a more comprehensive understanding of the scientific discourse landscape on safety management in the construction industry. Scopus contains a more recent and broader range, up to 20% more coverage than the Web of Science (Chadegani et al., 2013). In this study, bibliometric analysis of safety management in the construction industry was conducted through data collection and analysis of the most relevant keywords such as "management," "construction," and "safety." The search focused on title, abstract, and keywords. In addition, the boolean operator "AND" was utilized to demonstrate a strong focused research range of publications in safety management in the construction industry.

Third (Filtering), exporting data from the Scopus database, the filter was utilized by subject areas, institutions, co-citations, chronological, and geographical concepts. The language filter was "English" to exclude irrelevant research results. There was no limitation by country. Central to the study design is the critical decision concerning the temporal scope, with the chosen timeframe from 2000 to 2023, because after 2000, there was a rapid increase in publications. This period is pivotal for comprehensively capturing the field's evolutionary trajectory and developmental dynamics, facilitating a nuanced analysis of trends, shifts, and advancements over the delineated timeframe.

Fourth (Data visualization and analysis), VOSviewer was selected as the primary analytical tool for a network mapping approach, allowing for the representation of diverse metrics such as co-authorship networks, keyword co-occurrence networks, and institutional collaborations. Its efficacy in conducting bibliometric analyses is critical, particularly in visualizing and exploring complex networks of scientific literature. The study used search parameters such as titles, abstracts, and authors' keywords in academic publications, co-citation analysis, and cluster analysis, allowing for maximum coverage of diverse literature while minimizing the risk of missing important research in the respective field and analyzing current research trends. Additionally, network graphs and cluster maps were selected as appropriate visualization methods within color coding for timelines and fields of study.

The final stage of the bibliometric analysis (Interpretation) involves explanation of all data acknowledged from the analysis results in the form of a summary of research results. This stage reveals the structural characteristics of leading countries and institutions, key subject areas, networks, research trends, and authors, clustering scholars discussing safety management in construction industry.

3. RESULTS AND DISCUSSION

Construction safety management is actions that managers at all levels can take to create an organizational setting in which workers will be trained and motivated to perform safe and productive construction work (Levitt & Samelson, 1986).

Based on the Scopus database, 15,496 documents studied construction safety management in the period 2000–2023 (Figure 1).

The dynamics of indexed publications in the Scopus database reflect a growth in the number of publications from 2000 to 2022. Peak years for this dynamic were observed in 2012, 2020, and 2022. The majority of these documents were published after 2020, indicating a rapidly growing tendency for research and literature development in this area.

Next, bibliometric analysis focused on the author's countries to identify the geographical distribution of research contributions in the field of construction safety management.

According to Figure 2, China leads in publications with 4,737 (26.1% of the total), reflecting its significant surge in manufacturing and the largest

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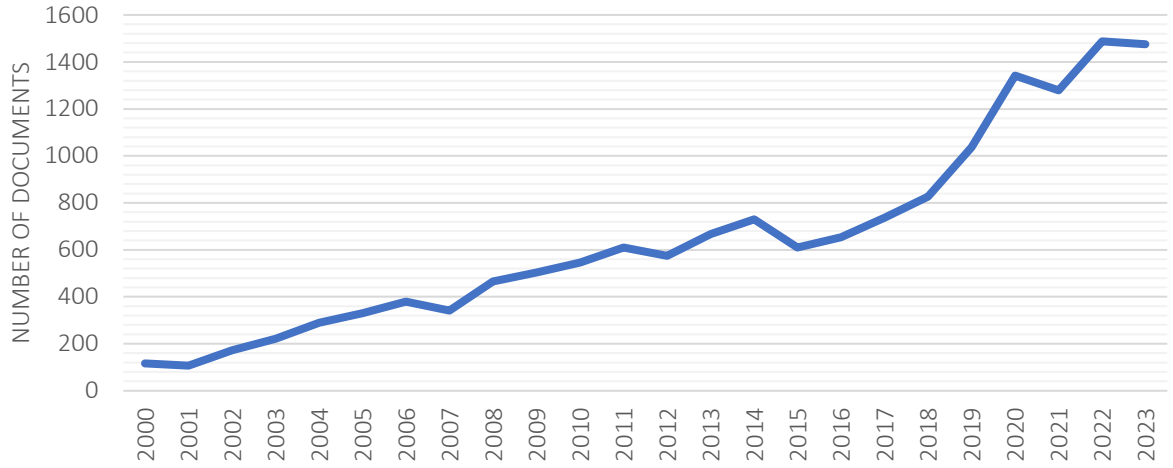

Figure 1. Dynamics of Scopus-indexed publications with the keywords "construction," "management," and "safety" during 2000–2023

building market, representing 20% of global construction investments. China's construction sector is expected to spend nearly USD 13 trillion on buildings by 2030. The United States follows with 2,558 publications (14.1%). The top four countries – China, the United States, the United Kingdom, and Australia – account for 50.2% of all publications, while other countries contribute around 2%. This highlights the significant contributions of China and the United States to construction management and safety research.

Figure 3 illustrates the major fields in safety management in construction industry landscape. Engineering, computer science, and ecology account for 49.3% of publications, highlighting researchers' focus on developing new technologies and methods for construction safety. Moreover, construction safety also involves social, psychological, and medical factors, such as human behavior and workers' psychological state, which can affect health and safety outcomes (Social sciences and Medicine showed 7.3% and 7.0%, respectively).

The results of the bibliometric analysis also allow for the identification of the most active keywords based on their appearance frequency in the sample, particularly according to parameters such as occurrences (the frequency of appearance of keywords in document titles and abstracts) and relevance (scales from 0 to 1, measuring the relevance of a term to the keywords and topic). In Table 1, the most relevant keywords are safety climate, safety behavior, and building information modeling. Keywords that frequently appear in scientific publications

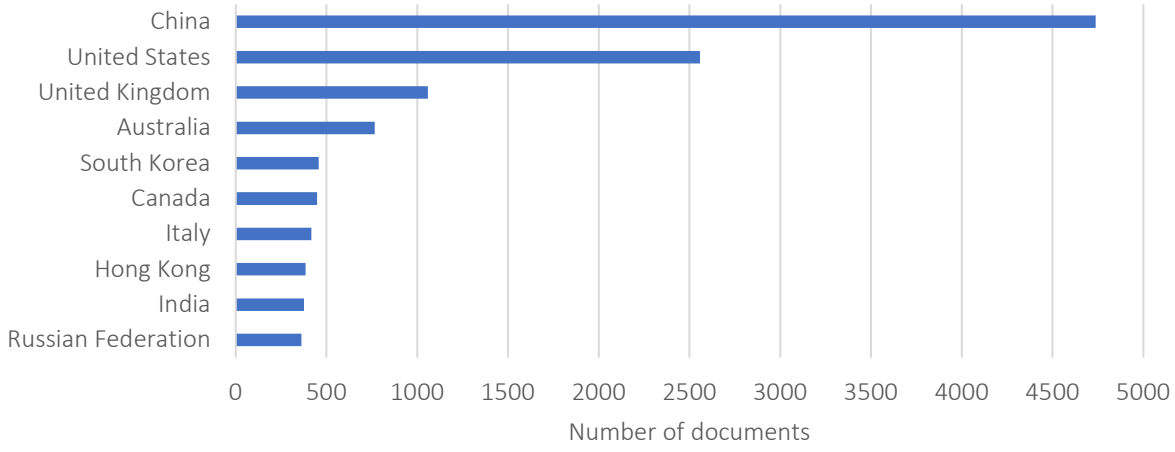

Figure 2. Top 10 countries with the highest counts of scientific documents under keywords "construction," "management," and "safety" in 2000–2023

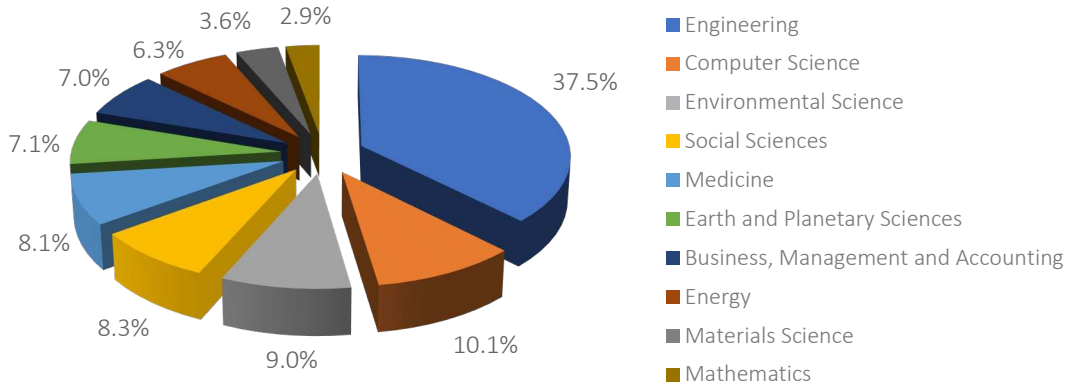

Figure 3. The subject structure of scientific publications based on the keywords "construction," "management," and "safety" in the Scopus bibliometric database from 2000 to 2023

during the investigated period include realization (Occurrences – 218), building information modeling (Occurrences – 198), and management process (Occurrences – 181). This underscores the importance of considering key factors such as climate and ecosystem and proper organization, including worker training in safety techniques and process management with guarantees and a high level of traceability. There is a linear correlation between the frequency of keywords and their overall strength.

Table 1. List of most active keywords on safety construction management

	Keywords	Occurrences	Relevance
1	Safety climate	175	0.62
2	Safety behavior	197	0.61
3	Building information modelling	198	0.50
4	Traceability	147	0.50
5	Intelligent management	152	0.49
6	Management process	181	0.48
7	Things technology	162	0.46
8	Realization	218	0.30
9	Ecosystem	166	0.30
10	Guarantee	257	0.29

Table 1 provides a comprehensive list of the most used keywords in safety construction management, offering insights into the predominant terms shaping research in this field. These keywords serve as pivotal markers in understanding the discourse surrounding safety within construction management.

The next type of analysis is chronological, which covers the temporal evolution of scientific publications. Figure 4 illustrates this chronological investigation and historical trends in the field of construction safety management.

As mentioned earlier, the initial selections were from 2012 and earlier, with another focus on 2020. The technical algorithms utilized by VosViewer reveal variations in research activity following these peak periods. Consequently, for author mapping, a chronological snapshot spanning from 2012 to 2020 was presented, especially considering the active involvement of Chinese research during this period. In continuing, topic mapping concentrated on the period after 2020, reflecting the significant portion of investigations attributed to China.

Based on the results of spatiotemporal bibliometric analysis, the intensification of research on financial decentralization issues occurred worldwide during the period from 2012 to 2018 within three consecutive time intervals, each with its own geographical centers. The visualization map provides a comprehensive overview of the evolving research landscape, delineating shifts in emphasis and geographical distribution over time in the country-time dimension of research concerning construction safety management (Figure 4). The analysis depicts trends and patterns across different temporal periods. Meanwhile, notable contributors to research in construction safety management until 2014 encompassed the United States,

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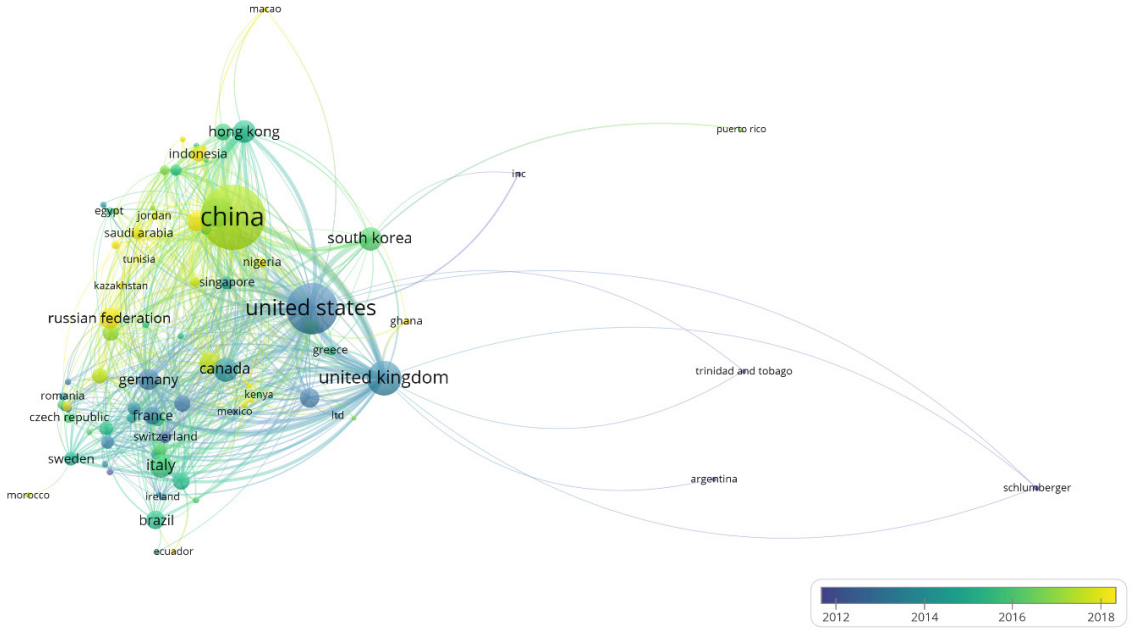

Figure 4. Visualization map of the country-time dimension of research on issues of construction safety management according to data from the Scopus database in 2012–2020

the United Kingdom, Germany, France, Canada, and Argentina. During the subsequent period from 2014 to 2016, a discernible shift in research focus occurred, with increased investigation observed in Hong Kong, Italy, Sweden, Brazil, the Czech Republic, Romania, and South Korea. Since 2018, a significant transition has been witnessed, characterized by heightened research activity in countries including China, Indonesia, Saudi Arabia, and Israel. These nations have emerged as pivotal hubs driving advancements and addressing pertinent challenges within the realm of construction safety management.

Figure 5 delineates a visualization map portraying the scientific co-authorship structure of research in

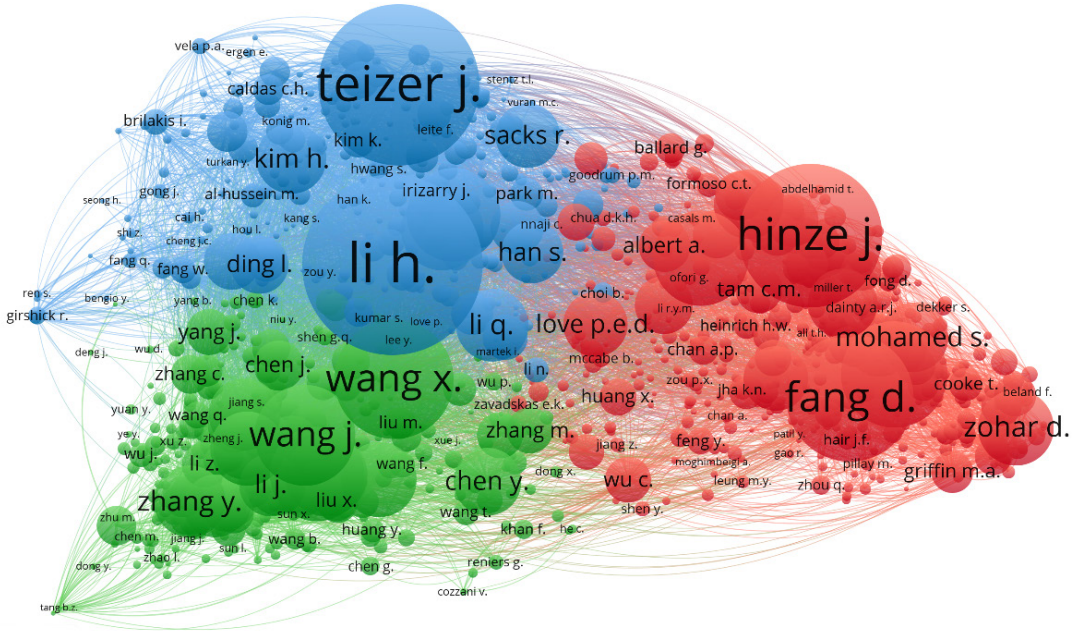

Figure 5. Visualization map of the scientific co-author's structure of research of safety management in construction in 2000–2023

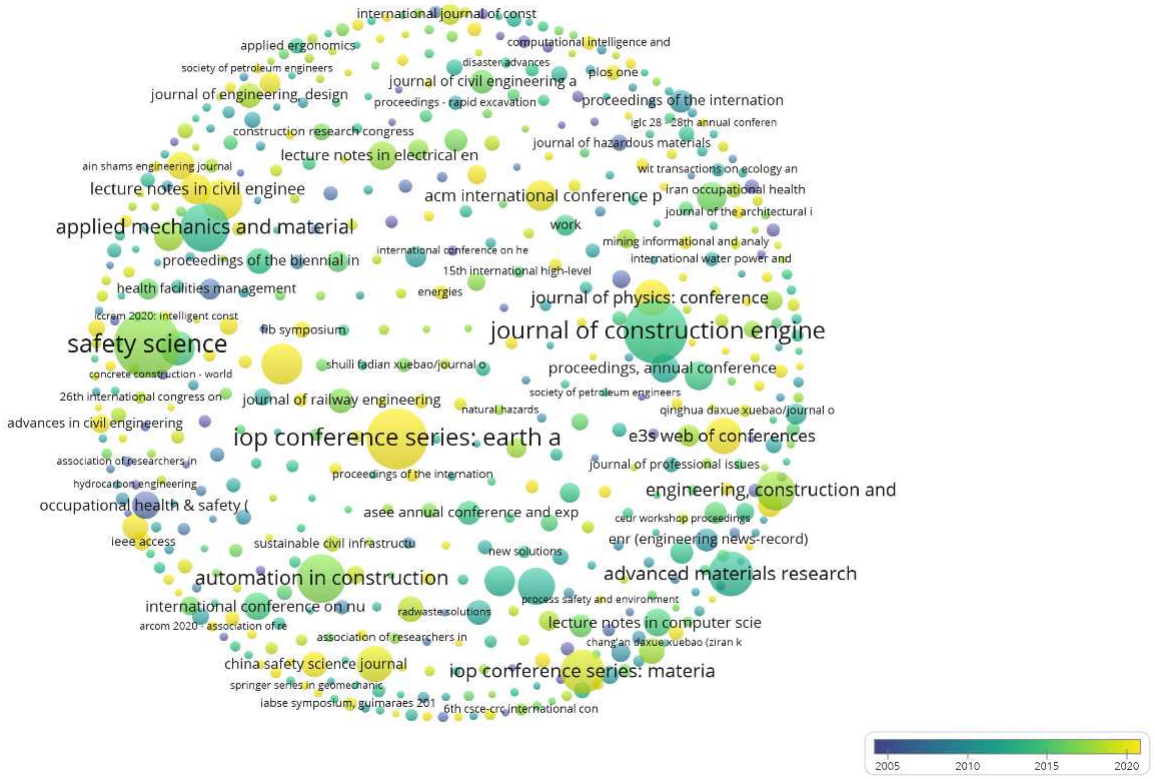

Figure 6. Visualization map of the co-citation by scientific fields and journals of research on issues of safety management in construction in 2000–2023

the realm of construction safety management. In this domain, noteworthy contributions emanate from Li H. (Saudi Arabia), Teizer J. (Germany), Sacks R. (Israel), and Kim H. (South Korea). Concurrently, in the sphere of innovation and project management, significant figures encompass Wang X. (Sydney), Wang J. (China), along with Zhang Y. and Chen Y. (Canada). Moreover, the domain of safety management studies witnesses enriched scholarly contributions from Fang D. (China), Hinze J. (the US), and Zohar D. (Israel), signifying their pivotal role in advancing knowledge and understanding within distinct domains of safety management.

The co-authors' structure depicted in Figure 5 complements the co-citation analysis presented in Figure 6, providing a comprehensive overview of the collaborative networks and scholarly engagement within the research landscape of construction safety management in the last 23 years.

A visualization map demonstrates the co-citation patterns by scientific fields and journals in the research landscape of construction safety management (Figure 6). The majority of scientific research output is published in journals, including the Journal of Construction and Engineering, Safety Science Journal (2016), Journal of Automation in Construction and Applied Mechanics and Materials (2014), Journal of Physics, Automation in Construction, and Occupational Health and Safety (2005), as well as the IOP Conference Series Earth and Environmental Science (2020). These prominent journals serve as significant contributors to the co-citation network, reflecting the collaborative interplay and cross-disciplinary engagement within the field of construction safety management.

The next step is a visualization map of the institutions and departments' dimensions of research on issues of construction safety management (Figure 7).

In Figure 7, the essential contributors are the University of Chinese Academy of Sciences, the Department of Building and Real Estate at Hong

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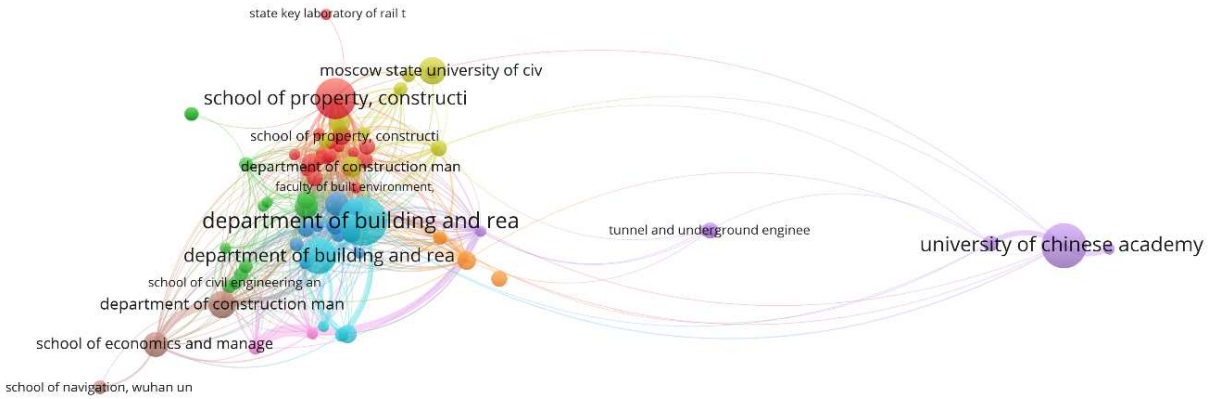

Figure 7. Visualization map of the institutions and departments dimension of research on issues of construction safety management according to data from the Scopus database in 2000–2023

Kong Polytechnic University, and the School of Property, Construction, and Project Management at the Royal Melbourne Institute of Technology. China's focus on tunneling and underground engineering is highlighted by the Development and Expectation of Tunnel and Underground Engineering Technology. Other significant contributors are the Department of Construction Management at the School of Economics and Management and the State Key Laboratory of Hydraulic Engineering Simulation and Safety at Tianjin University. These institutions collectively drive advancements in construction safety standards and practices.

The next step of investigation is cluster analysis, which visualization is demonstrated in Figure 8.

Figure 8 elucidates trends such as technological advancements in project management within the construction industry, considerations for sustainable development, discussions on workplace safety protocols, and investigations into clinical root cause analyses.

The following step is a breakdown of five identified key clusters categorized pertinent to safety in the construction industry and engineering in conjunction with project planning, as well as an exploration into the ramifications of hazardous occupational exposures. Other considerations entail risk and human factors management within the construction domain, sustainable development initiatives, and environmental factors (Table 2). This cluster includes searching for qualified la-

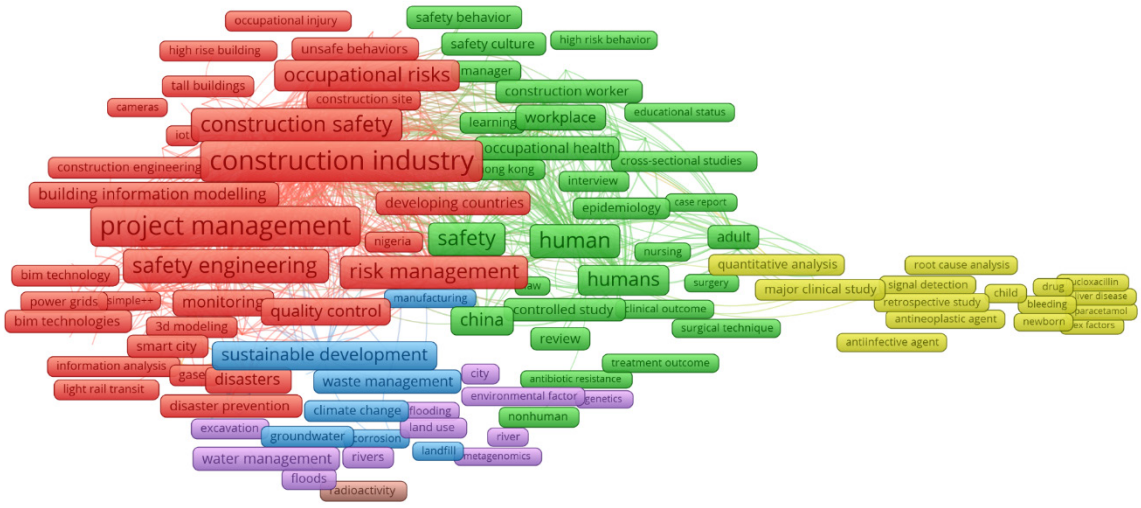

Figure 8. Cluster analysis of publications indexed in Scopus in the context of construction safety management from 2000 to 2023 using VosViewer

bor in safety rules, monitoring, and management. Each cluster delineates a distinct domain of inquiry within safety construction management, indicative of the interdisciplinary nature of research within this sphere.

The first cluster (red) concentrates on the construction industry and engineering facets with a focus on risk management, alongside the integration of advanced technologies such as Building Information Modeling (BIM), 3D modeling, and initiatives related to smart cities. This cluster delves deep into the utilization of cutting-edge tools and methodologies to optimize project efficiency and mitigate potential risks.

The second cluster (green) directs attention toward risk management at the construction level, with a specific emphasis on human factors management across diverse occupational roles and associated levels of safety education. Within this domain, attention is directed toward the diverse occupational roles present within the construction sector, with a keen eye on enhancing safety education and fostering a culture of risk awareness. This cluster seeks to bolster safety standards and minimize on-site incidents.

The third cluster (blue) encompasses investigations into sustainable development within safety management, spanning the construction and manufacturing sectors while considering the implications of climate change and groundwater dynamics. Researchers delve into the intricate interplay between sustainable practices and safety protocols across both the construction and manufacturing sectors. This cluster explores the ramifications of climate change and dynamic groundwater dynamics on safety measures, offering insights into how sustainable approaches can be seamlessly integrated into existing safety frameworks to promote long-term resilience and environmental stewardship.

The fourth cluster (violet) addresses how construction affects the environment, particularly pertaining to the management of land and water resources, which wield significant influence in guaranteeing safety and sustainability within construction endeavors. Such technologies as green buildings can reduce costs and the negative environmental impact of construction (for instance, the construction industry is responsible for 40% of global CO2 emissions), improving ecological safety.

The last cluster (yellow) is dedicated to research concerning the consequences of hazardous occupations in construction, which can lead to various diseases such as liver disease and cancer. Moreover, it explores strategies for the prevention and treatment of such health hazards. The yellow cluster includes specific scientific terms in keywords such as antiinefective agent and antineoplastic agent. Antiinfective agents are medicines that work to prevent or treat infections; they include antibacterials, antivirals, antifungals, and antiparasitic medications (Pfizer, n.d.). Antineoplastic agents (anticancer or hazardous drugs) are medications used to treat cancer.

The cluster analysis revealed several major trends within the domain of safety management in construction. These trends prominently encompassed risk reduction strategies, insights into human behavioral dynamics, considerations of occupational health, integration of sustainability practices, and initiatives focused on environmental prevention. Each of these thematic clusters provides distinct vantage points for understanding and addressing the multifaceted challenges inherent in ensuring safety within construction contexts.

This bibliometric analysis, based on 15,496 Scopus-indexed scholars during 2000–2023, is broader and more current than previous studies by Zhu et al. (2023), who analyzed 210 articles covering 1997–2020, and Otitolaiye and Abd Aziz (2024), who examined 799 documents from 2001 to 2021. This study found that China leads in safety management publications in the construction industry, contributing 20% of global output, with China, the US, the UK, and Australia together accounting for 50.2%.

Key research hubs in 2000–2023 include the University of Chinese Academy of Sciences, Hong Kong Polytechnic University, Royal Melbourne Institute of Technology, and Tianjin University. Otitolaiye and Abd Aziz (2024) highlighted other major contributors like Universiteit Gent, Wageningen University & Research, and Delft University of Technology.

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Table 2. List of key clusters in safety construction management

Cluster	Description	Keywords
Red	The cluster pertains to the safety construction industry and engineering-associated project planning, including risk management arising from hazardous employee behavior or disasters for risk prevention. It also involves the development of advanced technologies in the construction sector (e.g., building information modelling, BIM technology, 3D modelling, smart city, power grids, cameras)	construction industry, construction engineering, construction safety, safety engineering, risk management, occupation risks, occupation injury, project management, unsafe behavior, disasters, disaster prevention, building information modeling, bim technology, 3d modeling, smart city, power grids, cameras, quality control
Green	The cluster involves risk and human factors management in construction, among various occupations, their level of safety education and behavior	human, safety, safety behavior, high-risk behavior, workplace, construction worker, manager, learning, educational status, treatment outcome, occupation health
Yellow	The cluster is dedicated to researching the consequences of hazardous occupations in construction leading to various diseases ("liver disease," cancer) and approaches for preventing these conditions and their treatment	major clinical study, quantitative analysis, root cause analysis, liver disease, ex factors, antiinefective agent, antineoplastic agent, drug, paracetamol
Blue	The cluster encompasses studies in sustainable development in safety management in construction and manufacturing, considering the impact of climate change and groundwater movements	sustainable development, waste management, manufacturing, climate changes, groundwater, landfill
Violet	The cluster is associated with environmental factors, particularly land and water resource management	environmental factor, land use, city, excavation, water management, flooding, river, floods, generics

This global analysis covers various management articles, while Luo et al. (2022) focused on climate-related safety management in developing countries. These findings emphasize sustainable development and advanced technologies like building information modeling and 3D modeling for risk assessment. In contrast, Zhu et al. (2023) advocate for artificial intelligence and big data to improve safety design accuracy.

This study identified key trends in safety management, including risk reduction, human behavior analysis, occupational health, sustainable practices, and digital technologies. Akinlolu et al. (2020) found similar trends but with a narrower scope. This paper underscores the need for safety standards addressing environmental and health risks, aligning with Det Udomsap and Hallinger's (2020) focus on integrating sustainable development into safety protocols.

CONCLUSION

The dynamics of indexed publications reflect growth in the number of publications during the last 23 years, with the strongest connections between the construction industry and safety management with the human factor and project management within safety engineering with measurements. The major fields are engineering, computer science, and environmental science (49.3% of total research output). Geographical analysis identifies that China makes the greatest contribution, with 4,737 incidents, or 26.1% of the total articles. Notably, three distinct time intervals emerge: until 2014, characterized by the US, UK, Germany, France, Canada, and Argentina; from 2014 to 2016, featuring Hong Kong, Italy, Sweden, Brazil, the Czech Republic, Romania, and South Korea; and since 2018, with a shift toward China, Indonesia, Saudi Arabia, and Israel.

Cluster analysis of safety management trends in the construction industry highlights a pressing need to prioritize sustainable development in construction, encompassing initiatives such as the adoption of sustainable construction methods, implementation of waste reduction strategies, and concerted efforts toward environmental conservation. Additionally, investing in cutting-edge technologies plays a pivotal role in enhancing safety management practices, with advancements such as building information modeling technology and 3D modeling offering transformative potential in risk assessment and mitigation

strategies. Furthermore, there is a recognized imperative for private companies and construction management entities to bolster educational programs on occupational health, thereby equipping workers with the necessary knowledge and skills to navigate potential hazards effectively.

AUTHOR CONTRIBUTIONS

Conceptualization: Khanlar Ganiyev, Shahla Alizada.
Data curation: Anar Asgarov, Murad Gasimli, Nail Gasimzade.
Formal analysis: Khanlar Ganiyev, Shahla Alizada, Anar Asgarov.
Funding acquisition: Murad Gasimli, Nail Gasimzade.
Investigation: Khanlar Ganiyev, Shahla Alizada, Murad Gasimli.
Methodology: Khanlar Ganiyev, Shahla Alizada.
Project administration: Khanlar Ganiyev, Shahla Alizada, Anar Asgarov, Nail Gasimzade.
Resources: Khanlar Ganiyev, Murad Gasimli.
Software: Anar Asgarov, Murad Gasimli, Nail Gasimzade.
Supervision: Khanlar Ganiyev, Shahla Alizada.
Validation: Anar Asgarov, Murad Gasimli, Nail Gasimzade.
Visualization: Anar Asgarov, Murad Gasimli, Nail Gasimzade.
Writing – original draft: Shahla Alizada, Anar Asgarov.
Writing – review & editing: Khanlar Ganiyev, Murad Gasimli.

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