frontiers | Frontiers in Built Environment

TYPE Review
PUBLISHED 30 April 2025
DOI 10.3389/fbuil.2025.1602297

Unveiling construction accident causation: a scientometric analysis and qualitative review of research trends

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RECEIVED 29 March 2025
ACCEPTED 22 April 2025
PUBLISHED 30 April 2025

CITATION
Zang H, Li M, Jin Z and Huang J (2025) Unveiling construction accident causation: a scientometric analysis and qualitative review of research trends.
Front. Built Environ. 11:1602297.
doi: 10.3389/fbuil.2025.1602297

The construction industry, a cornerstone of global economic growth, faces frequent safety accidents due to its complex environments and multi-party collaboration, impeding sustainable development. These incidents arise from interlinked causal factors, including human error, management shortcomings, technical failures, and environmental conditions. This study systematically reviews construction accident causation research by integrating scientometric analysis and qualitative methods, using VOSviewer to analyze literature from Scopus and Web of Science databases, with 110 peer-reviewed articles selected through a validated Boolean search strategy. VOSviewer was used for bibliometric visualization to map research trends, co-authorship networks, and keyword co-occurrences. In addition, a qualitative synthesis was conducted to review common data sources and examine key issues, including risk factor identification, accident type classification, causality analysis, and the optimization of research strategies. The study aims to systematically review the current state of construction accident causation research, highlighting key trends in data-driven and AI-based safety interventions. Findings reveal a shift toward data-driven, intelligent approaches, with artificial intelligence techniques—such as large models (capable of understanding complex patterns from massive datasets), graph neural networks (suitable for modeling relationships between contributing factors), and natural language processing (for extracting insights from textual accident reports)—enhancing accident prevention and risk prediction. Challenges persist, however, in data quality, causal exploration depth, and interdisciplinary integration. These findings underscore the need for further advancements in data accuracy and model scalability, which could inform more effective safety management practices and policy frameworks. Key contributions include filling the bibliometric gap in this field, offering a novel framework combining quantitative and qualitative insights, and highlighting advanced technology applications, thus providing theoretical and practical guidance for future safety management. Future research is recommended to leverage AI, foster interdisciplinary collaboration, and develop precise prevention systems to address these gaps.

KEYWORDS

risk assessment, construction safety, construction accident causality analysis, scientometric analysis, construction industry sustainability

1 Introduction

The construction industry serves as a fundamental driver of global economic growth and urbanization, playing a pivotal role in infrastructure development, urban expansion, and social progress. However, this sector is recognized as inherently high-risk, with a propensity for accidents that can result in severe injuries or fatalities. Establishing an accident-free environment is deemed a central challenge for achieving sustainable development within the industry (Zakaria et al., 2023). Dynamic site conditions, intricate process coordination, competing stakeholder interests, and variable worker competency levels are identified as factors that substantially elevate the likelihood of safety incidents. Globally, statistical evidence indicates that the construction industry sustains one of the highest rates of work-related fatalities, underscoring its persistent accident incidence (Ibrahim et al., 2021; Zhou et al., 2023). Such incidents inflict profound harm on victims and their families while imposing significant economic losses on enterprises, the industry, and society at large. Construction accidents are understood to arise from the interplay of multiple causal factors, where certain elements may trigger others, culminating in an incident (Yang et al., 2024). Identifying risk sources is regarded as a vital step toward accident prevention, with the assessment of these factors' impacts on safety risks considered equally critical (Alomari et al., 2020). Consequently, addressing and mitigating key causal factors is recognized as an urgent priority in construction accident prevention research.

Investigating the causes of construction accidents carries substantial academic and practical importance. These causes are multifaceted, encompassing human error, technical deficiencies, management shortcomings, and environmental influences. The effective identification and quantification of these factors' impacts are acknowledged as central academic pursuits (Chen N. et al., 2022). Practically, a thorough analysis of causal factors is seen to underpin construction safety management, facilitating the formulation of evidence-based prevention strategies, reducing accident likelihood, and elevating industry safety standards (Zhang, 2022). In-depth exploration of accident causation is thus viewed as essential for systematic risk factor identification and assessment, while also providing a foundation for refining safety management approaches. A robust safety management system is considered capable of substantially lowering accident rates, minimizing casualties and property damage, and supporting the sustainable advancement of the construction sector. While numerous studies have explored construction accident causation using diverse methodological approaches, there remains a lack of comprehensive reviews that systematically examine the evolution, strengths, and limitations of these methods. Existing literature often adopts singular analytical techniques or focuses on specific cases, making it difficult to form an integrated understanding of methodological developments and to identify emerging trends or opportunities for innovation in this field. This review aims to systematically examine the evolution of research on construction accident causation by integrating scientometric and qualitative approaches, in order to identify key causal factors, analyze their interrelationships, and explore emerging trends and methodological innovations in the field.

In recent years, advancements in data analysis and literature review tools have positioned bibliometric analysis as a valuable method for systematically mapping research hotspots, knowledge networks, and emerging trends in academia. Bibliometric indicators are employed to assess scientific output, explore science-technology interactions, delineate knowledge domains, and trace the evolution of new knowledge, offering insights for strategic planning and competitive positioning (Al Husaeni, 2023). Citation visualization analysis, a key bibliometric technique, has evolved within scientometrics and data visualization to depict interdisciplinary relationships and research patterns through knowledge maps (Chen et al., 2016). Among available tools, VOSviewer is widely adopted across disciplines for its robust visualization and analytical capabilities, enabling the construction of maps via mapping techniques and multidimensional scaling (Rusydiana et al., 2021). This software is utilized to illustrate research topic evolution, institutional and scholarly collaboration networks, and the distribution of prominent research areas, establishing a strong basis for further investigation.

Despite the widespread application of bibliometric methods across various fields (Huang et al., 2022), their use in construction accident causation research remains underexplored. However, no existing study has systematically mapped the knowledge structure of this domain while concurrently evaluating methodological developments and practical trajectories in an integrated manner. Given the interdisciplinary complexity and multidimensional interactions inherent in this domain, bibliometric approaches are seen as well-suited to holistically review its research landscape, uncovering hotspots, gaps, and trends related to key causal factors. Additionally, this methodology is recognized for its ability to highlight influential literature and prominent scholars, fostering academic collaboration and informing research direction decisions. Furthermore, bibliometric analysis is valued for clarifying the thematic structure and developmental trajectory of construction accident causation studies, providing an objective foundation for devising scientifically grounded prevention strategies and advancing both theoretical and practical dimensions of construction safety management. Accordingly, VOSviewer is employed in this study to perform a bibliometric analysis of construction accident causation literature, targeting research hotspots, collaboration networks, and high-impact works to elucidate the field's knowledge system and trajectory, thereby supporting subsequent research efforts. However, bibliometric methods alone often fall short in capturing the nuanced insights required for interpreting causality and practical relevance in complex fields like construction safety. Therefore, this study strategically combines scientometric analysis with a qualitative review to leverage the strengths of both methods: the former provides a macro-level overview of the research structure and trends, while the latter offers in-depth, contextual understanding of methodologies, causal logic, and technical applications. This mixed-methods approach enhances both the breadth and depth of analysis, allowing for a more comprehensive exploration of construction accident causation.

Construction project accidents represent significant incidents, necessitating detailed analysis to uncover their root causes (Betsis et al., 2019). Existing identification methods are systematically reviewed in this study, with their limitations evaluated and an innovative framework proposed. Accident types are scientifically classified to reveal causality patterns and evolutionary trends, offering a basis for precise prevention and

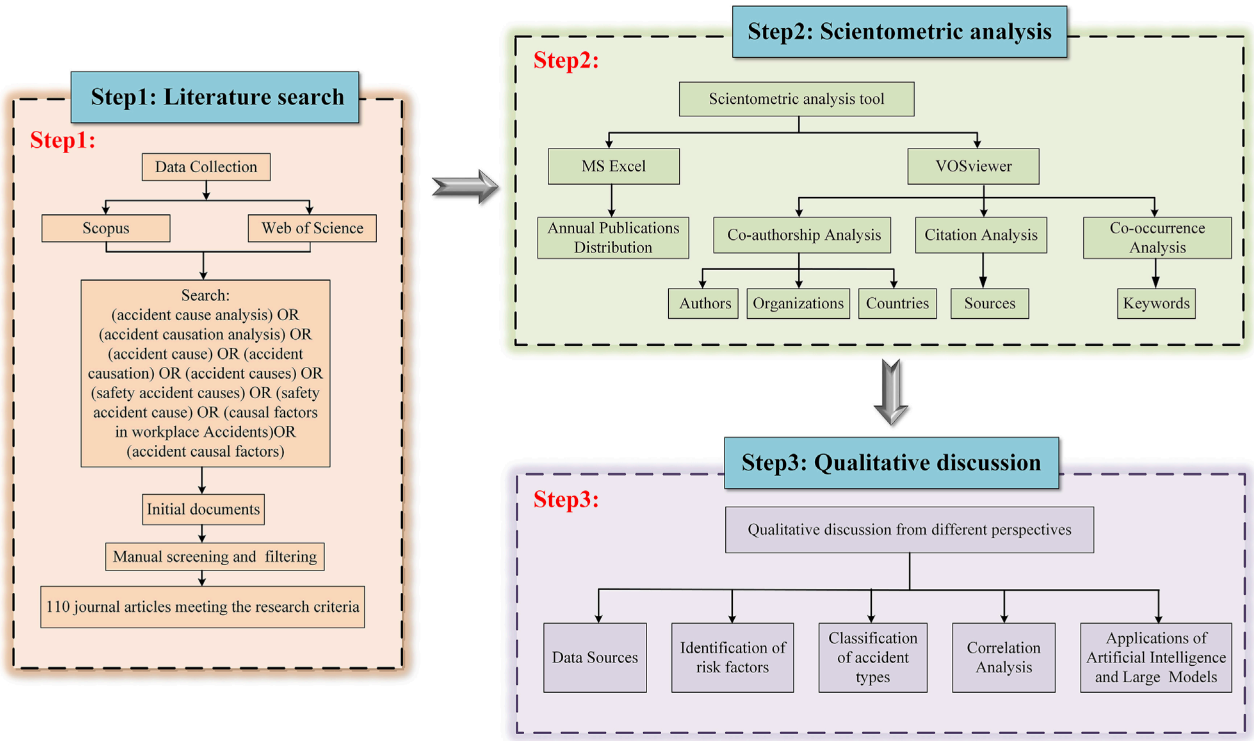

FIGURE 1
Research methods flowchart.

control measures. Correlation analyses of causal factors are examined to identify interactions and refine prevention strategies. The current applications of artificial intelligence and large-scale models are also assessed, with their strengths and limitations analyzed to explore future directions.

The structure of this paper is outlined as follows: Section 2 details the research methodology, encompassing literature retrieval, bibliometric analysis, and qualitative discussion processes; Section 3 presents the bibliometric analysis results, highlighting research trends, knowledge networks, and collaboration patterns; Section 4 provides a qualitative discussion that integrates quantitative findings, systematically addressing data sources, risk factor identification, accident type classification, factor correlations, and the role of artificial intelligence and large models in causation research, while evaluating limitations and future directions; Section 5 concludes with a summary of the findings.

2 Research methods

A scientometric mapping approach is employed in this study to develop a systematic evaluation framework using the widely used three-step approach (Wang et al., 2022a; Wang et al., 2024; Zhang et al., 2024; Fu et al., 2024): literature retrieval, bibliometric analysis, and qualitative discussion. The process is depicted in Figure 1.

During the literature retrieval phase, relevant data were sourced from the Scopus and Web of Science (WoS) databases to establish the research dataset. In the scientometric analysis phase, publication counts across years were statistically analyzed using MS Excel to uncover research trends. Subsequently, VOSviewer (Version 1.6.20) was applied for visualization analysis, generating a knowledge network to pinpoint research hotspots, track evolutionary trends, and evaluate significant contributions and academic influence. Informed by the scientometric findings, a qualitative discussion was conducted to examine key aspects of construction accident causation.

2.1 Literature search

The initial phase of this research involves selecting suitable databases and defining the retrieval strategy. A literature search was conducted using Scopus and WoS, targeting peer-reviewed journal articles in English. Keywords were applied across title, abstract, and keyword fields to ensure comprehensive coverage.

Given the broad scope of construction accident research, an extensive retrieval strategy was implemented. Literature published up to December 2024 was searched using the string: ("accident cause analysis" OR "accident causation analysis" OR "accident cause" OR "accident causation" OR "accident causes" OR "safety accident causes" OR "safety accident cause" OR "causal factors in workplace accidents" OR "accident causal factors").

The screening process was executed in stages. Initially, titles and abstracts were reviewed to exclude articles unrelated to construction or safety causation. After eliminating duplicates, the remaining articles' titles, abstracts, and select full texts were thoroughly evaluated to further refine the dataset.

Construction accidents are categorized by location—e.g., residential building sites, tunnels, or roads—reflecting distinctions noted in prior studies (Antoniou and Merkouri, 2021; Douglas and Adeloye, 2016). Infrastructure such as roads, bridges, and buildings is recognized as vital for national development (Zakaria et al., 2023). Thus, this study encompasses accidents across buildings, subways, tunnels, and bridges, aiming for a holistic analysis of causation to enhance safety management perspectives.

Following rigorous screening, 110 relevant journal articles were identified. The selection was based on a structured multi-stage screening process, incorporating relevance assessments, duplicate elimination, and inclusion criteria refinement, to ensure the quality and representativeness of the final dataset. Bibliographic data, including full records and references, were extracted for VOSviewer analysis, enabling the mapping of research hotspots, knowledge networks, and collaboration patterns to support construction accident causation analysis.

2.2 Scientometric analysis

The second phase entails scientometric analysis, a widely adopted method for field evaluation and visualization. Knowledge domains are mapped through this approach (Al Husaeni, 2023). Thematic trends over time were charted using Microsoft Excel to trace the literature's developmental path. VOSviewer was employed to explore collaboration networks among researchers, countries, and organizations, alongside keyword co-occurrence patterns.

Collaboration networks and thematic associations were generated using VOSviewer, analyzing interactions among research entities and their contributions. Co-authorship networks depict collaboration across researchers, countries, and organizations, while co-occurrence analysis reveals keyword relationships. These visualizations illuminate collaborative dynamics, knowledge diffusion, and key research areas, offering insights into the current state and future directions of construction accident causation research. This approach supports both quantitative and qualitative analyses of the field.

2.3 Qualitative discussion

The third phase involves a qualitative discussion aimed at organizing the literature, analyzing research content, and summarizing progress, challenges, and future trends in construction accident research.

Common data sources in causation analysis were systematically reviewed. Quantitative results from prior phases were integrated with relevant theories to examine risk factors, accident types, causal relationships, and emerging technology applications. Identification methods for accident causation were evaluated for applicability and limitations. Accidents were classified based on their characteristics to clarify typical causes and evolutionary patterns, providing a foundation for precise prevention. Causal relationship analysis methods from existing literature were reviewed, highlighting achievements in identifying causal chains and impact paths to inform prevention strategies. Current applications of artificial intelligence and large models were assessed, with their advantages, limitations, and future directions explored to advance intelligent safety management.

Grounded in systematic literature analysis and scientometric data, this discussion deepens the understanding of construction accident causation. Key issues are clarified, and references for theoretical and practical advancements are provided, supporting the optimization of safety management and accident prevention.

3 Analysis and findings

3.1 Publication outputs

A systematic retrieval and analysis of literature in the field of "construction accident causality analysis" was conducted for this review, aiming not only to illustrate quantitative growth but also to explore the underlying research dynamics and sociotechnical drivers behind the evolution. Publication trends from 1987 to 2024 are presented in Figure 2. The starting year of 1987 was selected as it corresponds to the earliest retrieved literature based on the specified search terms, marking the onset of documented studies in this domain.

In Figure 2, annual publication counts are depicted by a blue bar chart, cumulative totals by an orange line chart, and the cumulative trend by a green dashed line. Between 1987 and 2008, publication numbers remained low and increased slowly, possibly due to limited attention or scarce research resources during that period. A gradual rise in publications was observed from 2009, with a marked surge after 2012, likely driven by global construction industry growth, heightened focus on safety, and advances in research methodologies. A significant uptick in publications after 2019 was noted, potentially linked to increased construction accident frequency, growing societal awareness, and supportive policies. The cumulative publication count mirrors this upward trajectory, accelerating notably post-2019, reinforcing the field's rising significance. Figure 2 succinctly illustrates the publication growth in "construction accident causality analysis" from 1987 to 2024. The data highlight a steady increase in research interest, with accelerated activity in recent years, signaling the field's growing prominence in academia and practice. These trends offer insights into research dynamics, potential hotspots, and future directions, providing guidance for researchers and policymakers.

3.2 Co-authorship analysis

Research projects are often complex, necessitating multidisciplinary collaboration to ensure reliable and accurate outcomes (Kahn, 2018). Co-authorship network analysis is recognized as an effective approach for evaluating the novelty and collaboration dynamics of a research field. In this study, it also serves to identify influential scholars, collaborative clusters, and the disciplinary dispersion across institutions and countries. Collaboration scale and intensity are revealed, alongside interaction patterns among researchers. Home countries and affiliated institutions of collaborating authors are identified, shedding

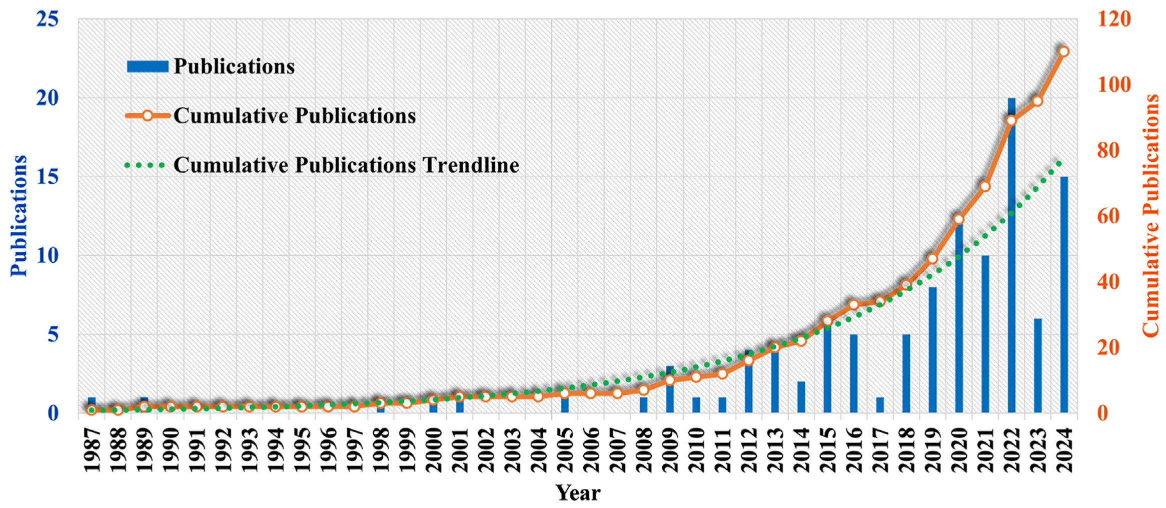

FIGURE 2
Publications growth over time.

light on cross-border and cross-institutional cooperation models. Such analysis provides quantitative evidence of globalization and collaboration in construction accident causality research, supporting future cooperation strategies.

3.2.1 Co-authorship authors

VOSviewer was utilized to analyze the co-authorship network of key authors in construction accident causality analysis, highlighting collaboration relationships and academic influence. Visualization results are presented in Figure 3. A threshold of at least two publications per author was applied, selecting 26 authors from an initial pool of 353 (Rusydiana et al., 2021). Nodes represent authors, with links indicating collaboration, their thickness reflecting intensity, node size denoting publication count, and color signifying average publication year. For instance, "Jianhong Shen," "Shupeng Liu," and "Jing Zhang" share an average publication year of 2024, indicating recent contributions aligned with current industry trends. The overall network density is low, suggesting limited integration across research teams. Most scholars contributed only one or two papers and lack sustained cooperation. This pattern reflects the field's current developmental stage, where cross-institutional and interdisciplinary collaboration is still emerging.

Citation count is widely regarded as an indicator of research quality (Martins et al., 2024). Key quantitative indicators for the top ten authors by citations are summarized in Table 1. "Ts Abdelhamid" (629 citations), "Chia-fen Chi" (159 citations), and "Michael Behm" (153 citations) demonstrate significant impact. In productivity, "Shengyu Guo" and "Bing Tang" each authored four papers, underscoring their notable contributions. Normalized citation metrics, adjusting for publication timing, highlight "Amir Mahdiyar," "Saeed Reza Mohandes," and "Tarek Zayed" for their impactful work within their respective periods.

3.2.2 Co-authorship country

International collaboration networks were analyzed using VOSviewer to map the global distribution and influence of construction accident causality research, with a focus on transnational knowledge exchange, policy diffusion, and regional research ecosystems, as shown in Figure 4. A threshold of one publication per country was set, including 33 countries. Nodes represent countries, with link thickness indicating collaboration strength. Quantitative indicators for the top nine countries by publication count are presented in Table 2. China, the United States, Australia, and South Korea lead in output and citations, reflecting robust research capabilities. High citation totals are noted for China, the United States, England, and Australia, with recent contributions from Malaysia, Poland, China, and Greece contrasting with earlier peaks (circa 2017) from the United States, England, and Australia.

3.2.3 Co-authorship institution

Collaboration networks among organizations were examined using VOSviewer, selecting 28 from 158 institutions with a minimum of two publications, as depicted in Figure 5. Nodes signify organizations, their size reflecting publication count, and link thickness indicating collaboration strength. Node color denotes activity level, with yellow indicating higher activity. Huazhong University of Science and Technology and China University of Geosciences exhibit strong inter-organizational ties, while Qingdao University of Technology and Wuhan University are notably active, with South China University of Technology also contributing significantly in recent years. However, international collaboration remains limited. Most institutional ties occur domestically within the same country or region. This indicates that while intra-national partnerships are well-developed—especially in China—transnational institutional collaboration is still in its infancy.

Quantitative indicators for the top eight organizations by publication count are summarized in Table 3, incorporating normalized citation metrics for fair impact comparison across time. Huazhong University of Science and Technology (7 publications, 296 citations), City University of Hong Kong (4 publications, 318 citations), Hong Kong Polytechnic University (4 publications, 148

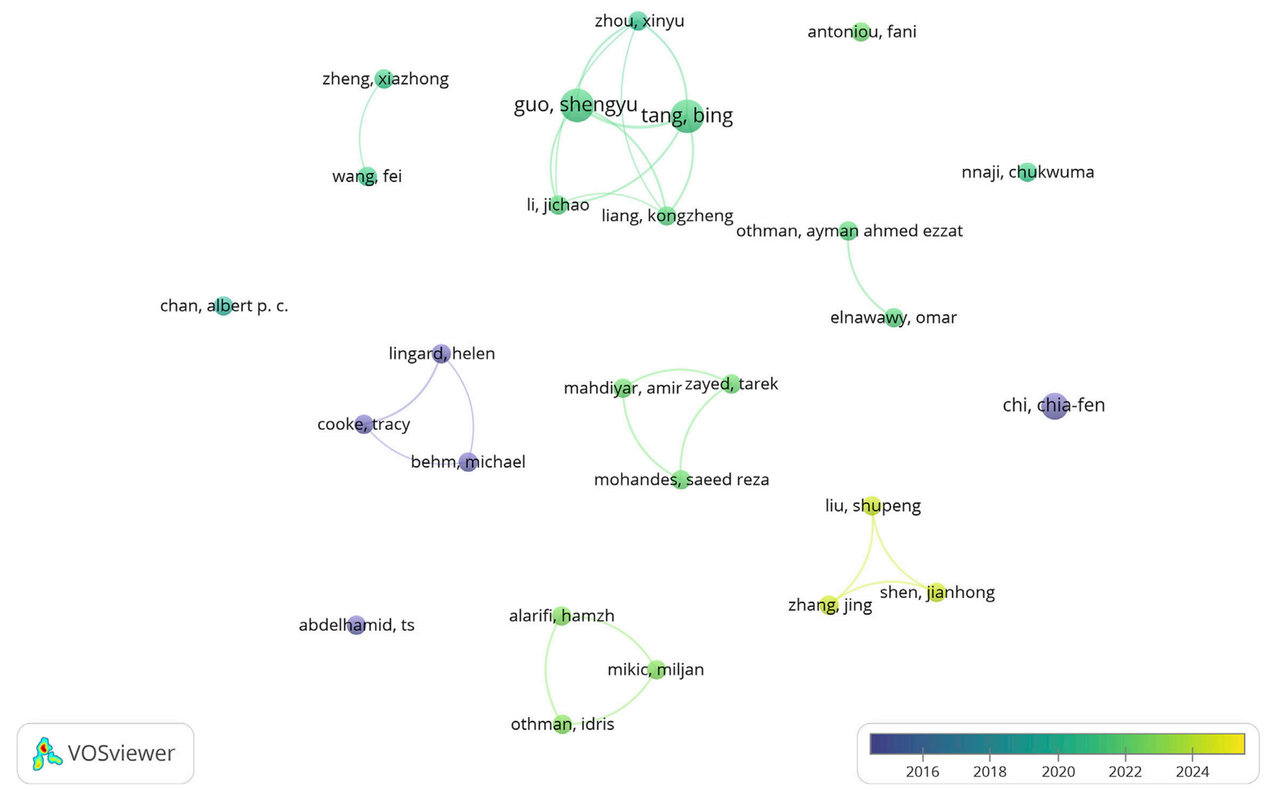

FIGURE 3
Co-authorship network for researchers.

citations), and China University of Geosciences (4 publications, 94 citations) stand out for productivity and influence.

3.3 Citation sources analysis

Cited journal analysis reveals connections among journals, aiding in the identification of key sources and the evolution of research hotspots. Using VOSviewer, a threshold of two publications per cited journal was set, selecting 21 out of 57 journals for analysis. A collaboration network diagram was generated, as shown in Figure 6. Nodes represent journals, with size indicating publication count and link thickness reflecting collaboration strength. The clustering patterns indicate interdisciplinary integration, especially between engineering management, safety science, and artificial intelligence.

In terms of collaboration, *Journal of Construction Engineering and Management* and *Safety Science* exhibit the strongest ties with other organizations' researchers. Node color denotes activity level, with yellow indicating higher activity. *Buildings* is identified as the most active, followed by *Expert Systems with Applications*, *Sustainability*, and *Applied Sciences-Basel*, reflecting their recent, trend-aligned contributions.

Quantitative indicators for influential journals are summarized in Table 4, ranked by publication count. *Journal of Construction Engineering and Management* (10 publications), *Safety Science* (8 publications), and *Engineering Construction and Architectural Management* (6 publications) emerge as leading contributors. Normalized citation metrics, adjusting for publication timing, highlight *Safety Science* and *Journal of Construction Engineering and Management* as having the most impactful papers within their periods.

3.4 Co-occurrence keyword

Keywords summarize research focus, and their analysis identifies hotspots and emerging topics (Yang et al., 2021). A co-occurrence network was constructed using VOSviewer, as shown in Figure 7, with a threshold of three appearances per keyword. Nodes represent keywords, with size proportional to frequency, link thickness indicating co-occurrence strength, and color reflecting clustering.

Five clusters are delineated in Figure 7, each highlighting distinct yet interconnected aspects of construction safety research. Cluster 1 (Red), the largest with 17 keywords, addresses "occupational safety," "risk assessment," "prevention," and "project management." This cluster emphasizes worker safety and performance in developing countries, with a focus on macroscale management and project-level safety controls. Cluster 2 (Green), with 13 keywords, explores "accident prevention," "behavioral risk chains," "complex networks," and "safety management models." This cluster integrates risk strategies and lifecycle accident perception analysis, emphasizing a systematic safety management model that merges behavioral

TABLE 1 Top authors ranked by citation count.

Author	Total citations	Number of publications	Average publication year	Average citations	Normalized citations	Average normalized citations
Ts Abdelhamid	629	2	2002	314.5	2	1
Chia-fen Chi	159	3	2011	53	2.4304	0.8101
Michael Behm	153	2	2013	76.5	2.6332	1.3166
Tracy Cooke	107	2	2014	53.5	2.0187	1.0093
Helen Lingard	107	2	2014	53.5	2.0187	1.0093
Shengyu Guo	94	4	2021	23.5	4.1996	1.0499
Bing Tang	94	4	2021	23.5	4.1996	1.0499
Amir Mahdiyar	83	2	2022	41.5	5.1728	2.5864
Saeed reza Mohandes	83	2	2022	41.5	5.1728	2.5864
Tarek Zayed	83	2	2022	41.5	5.1728	2.5864

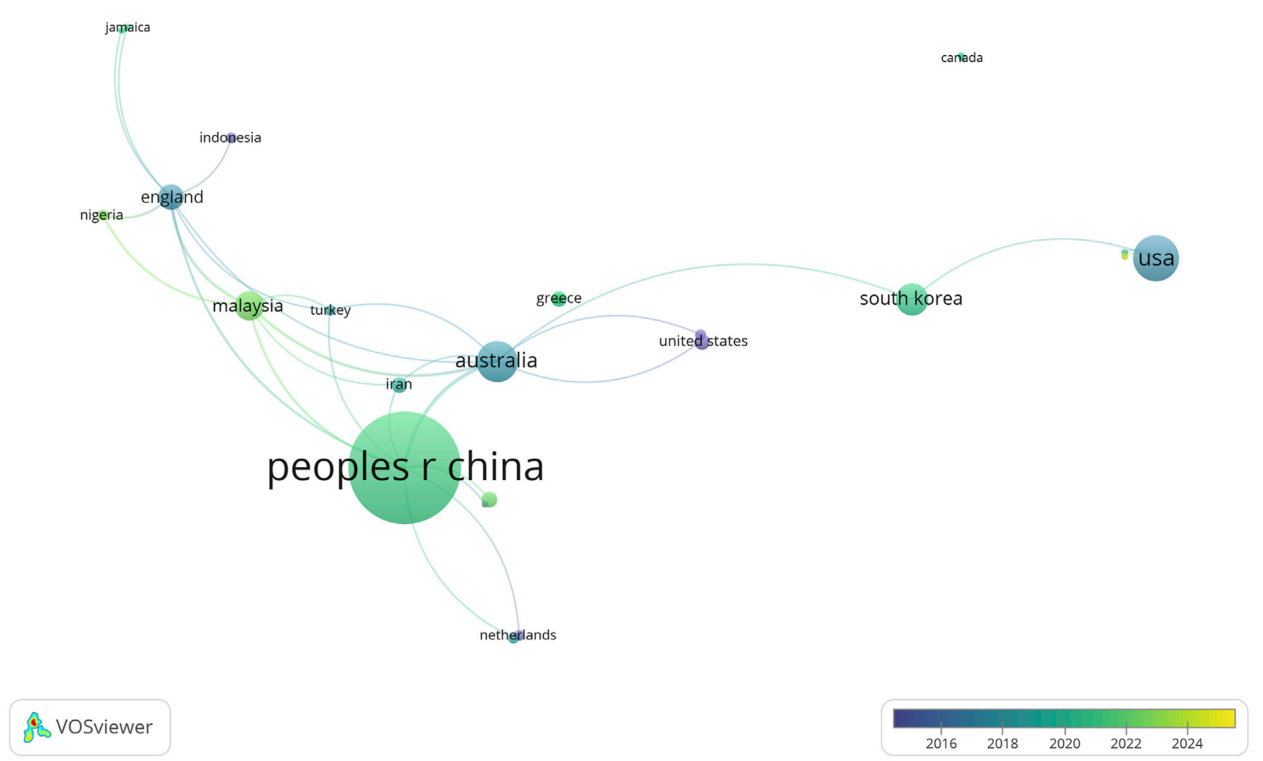

FIGURE 4
Co-authorship network for countries.

science with risk control. Cluster 3 (Blue), containing 11 keywords, focuses on “accident cause identification,” “behavioral analysis,” “machine learning,” and “natural language processing.” This cluster emphasizes data-driven approaches, using machine learning and natural language processing technologies to enhance site safety in a systematic manner. Cluster 4 (Yellow), with 10 keywords, examines “occupational injury causes,” “association rules,” and “safety patterns.” This cluster focuses on in-depth causal analysis,

TABLE 2 Top contributing countries ranked by publication count.

Country	Number of publications	Total citations	Average publication year	Average citations	Normalized citations	Average normalized citations
China	43	1,172	2021	27.26	49.41	1.15
United States	13	920	2017	70.77	14.24	1.10
Australia	11	462	2017	42	14.01	1.27
South Korea	8	194	2020	24.25	8.86	1.11
Malaysia	7	160	2022	22.86	11.07	1.58
England	6	490	2017	81.67	9.00	1.50
Iran	3	86	2019	28.67	4.48	1.49
Greece	3	32	2021	10.67	2.03	0.68
Poland	3	15	2022	5	3.41	1.14

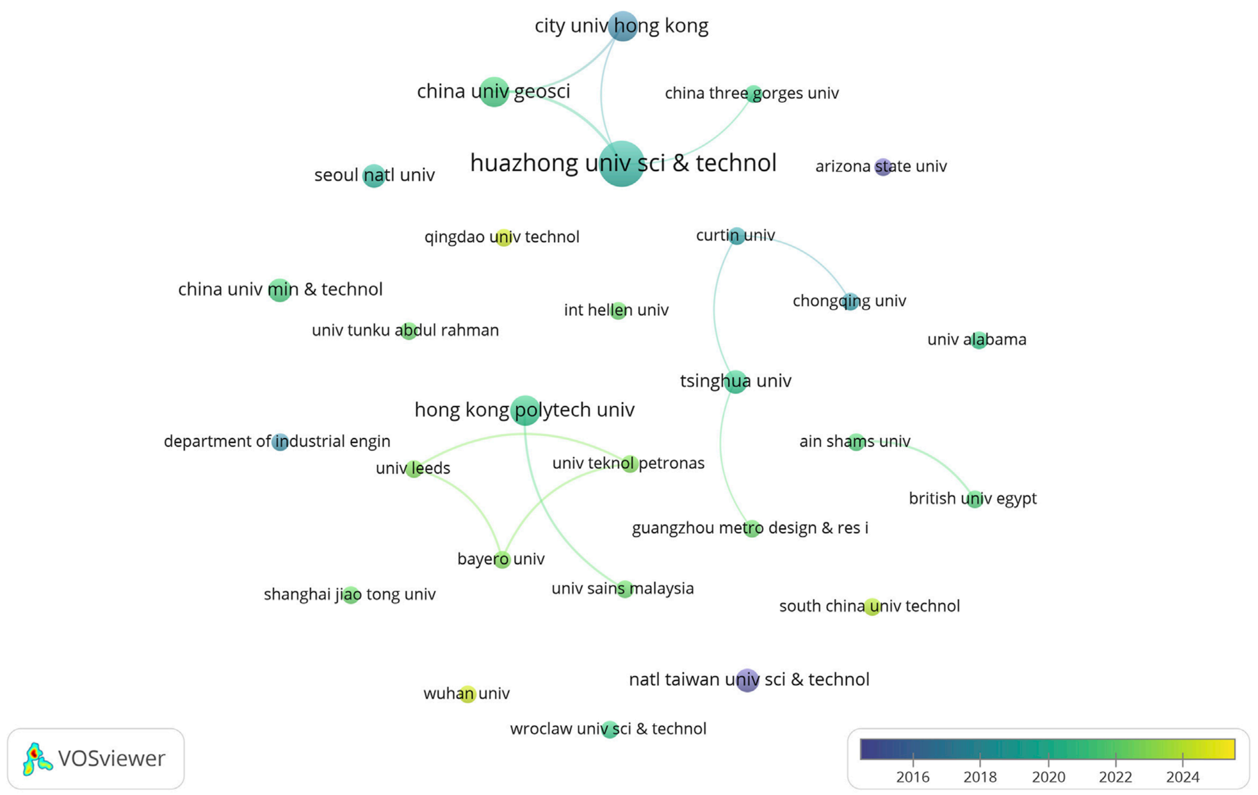

FIGURE 5
Co-authorship network for organizations.

particularly in regions like Taiwan, highlighting safety patterns and behavioral rules specific to these areas. Cluster 5 (Purple), the smallest with nine keywords, targets "accident analysis," "causal factors," "classification," and "design frameworks." This cluster focuses on design frameworks for safety improvements, exploring accident analysis and causal factor classification to drive more effective safety designs and management. These clusters, while distinct, exhibit interconnections that reflect the complexity and overlap in the field, offering a multidimensional perspective on research dynamics and trends to guide future hotspot identification.

TABLE 3 Top contributing organizations ranked by publication count.

Organization	Number of publications	Total citations	Average publication year	Average citations	Normalized citations	Average normalized citations
Huazhong University of Science and Technology	7	296	2019	42.28	10.43	1.49
China University of Geosciences	4	94	2021	23.50	4.19	1.04
City University of Hong Kong	4	318	2017	79.50	5.06	1.26
Hong Kong Polytechnic University	4	148	2020	37.00	6.77	1.69
Tsinghua University	3	140	2020	46.66	2.38	0.79
China University of Mining and Technology	3	98	2021	32.66	5.12	1.70
National Taiwan University of Science and Technology	3	159	2011	53.00	2.43	0.81
Seoul National University	3	147	2019	49.00	5.45	1.81

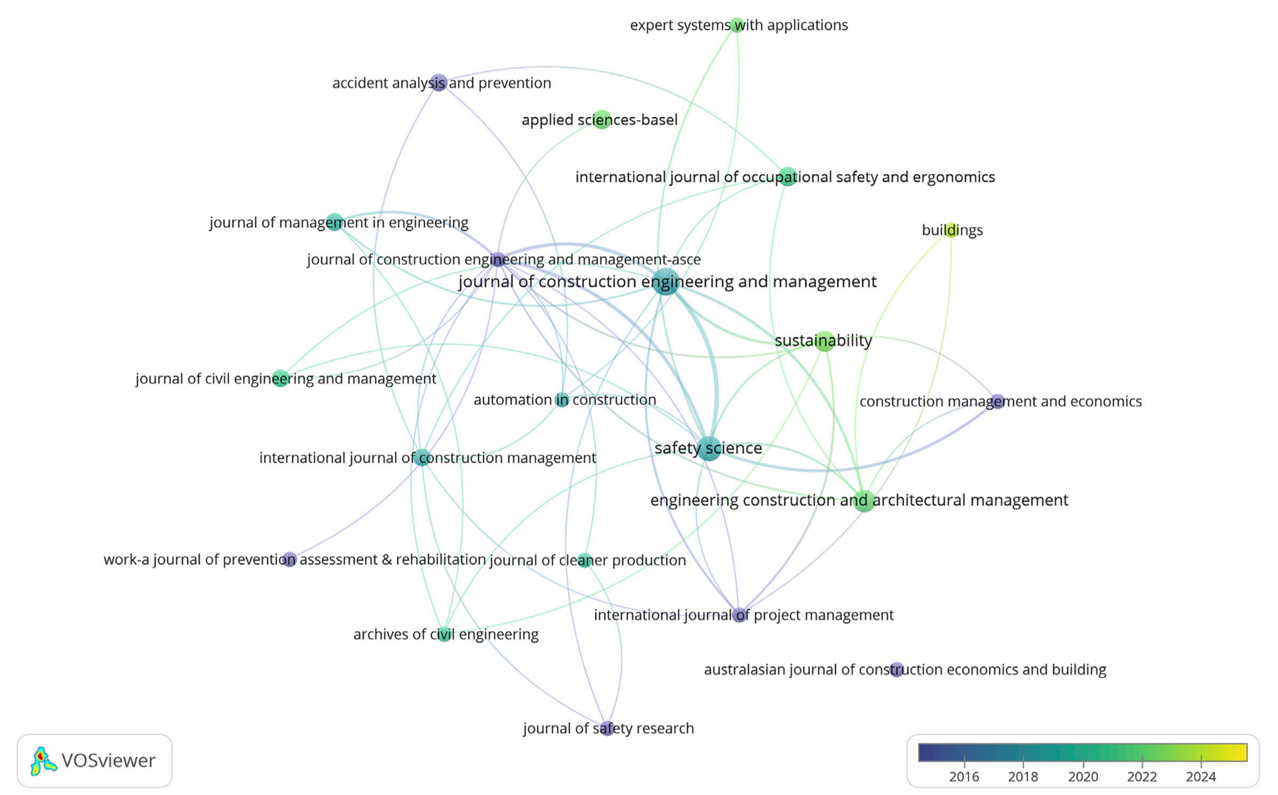

FIGURE 6
Citation network for sources.

TABLE 4 Top journals ranked by publication count.

Journals	Number of publications	Total citations	Average publication year	Average citations	Normalized citations	Average normalized citations
Journal of Construction Engineering and Management	10	547	2018	54.70	8.83	0.88
Safety Science	8	376	2018	47.00	14.50	1.81
Engineering Construction and Architectural Management	6	95	2021	15.83	6.10	1.01
Sustainability	5	35	2022	7.00	2.76	0.55
International Journal of Occupational Safety and Ergonomics	4	79	2021	19.75	3.25	0.81
Applied Sciences-basel	4	41	2022	10.25	3.01	0.75
Journal of Management in Engineering	3	223	2019	74.33	5.53	1.84
International Journal of Construction Management	3	61	2019	20.33	3.63	1.21
Accident Analysis and Prevention	3	116	2009	38.66	1.94	0.64
Journal of Civil Engineering and Management	3	28	2020	9.33	1.46	0.48

4 Qualitative discussion

The scientometric analysis conducted in the previous section offers a data-driven overview of the intellectual landscape in construction accident causation research. To further interpret and contextualize these findings, the following qualitative analysis delves into key thematic areas that have emerged as focal points across the literature. While informed by the clustering patterns and keyword co-occurrence trends, this part moves beyond citation metrics to explore the conceptual, methodological, and practical dimensions of the field. In doing so, it bridges the quantitative patterns with in-depth content analysis, offering a more nuanced understanding of research priorities, challenges, and developments.

Data sources are systematically organized in this section from a qualitative perspective, integrated with quantitative analysis results. Risk factor identification, accident type classification, and interrelationships among factors in construction accident causation studies are explored. Concurrently, the current applications and limitations of artificial intelligence and large models in this field are assessed, with future research directions outlined.

4.1 Data sources

The diversity and quality of data sources in construction accident causality analysis directly influence the scientific validity and reliability of findings. A thorough review of 110 relevant articles revealed reliance on varied sources, including questionnaires, expert interviews, literature reviews, field surveys, and accident investigation reports. Each source contributes significantly to uncovering accident causes, analyzing risk factors, and proposing enhancements. Accident investigation reports, compiled post-incident by authoritative agencies or professional teams, are distinguished as a primary source due to their detailed, comprehensive, and credible content, providing a robust basis for causal analysis and risk identification (Zhang J. et al., 2020). Acquisition methods for these reports and associated institutions across countries and regions are detailed in Table 5. However, it is worth noting that the reliability, consistency, and completeness of these data sources may vary across regions and institutions. Therefore, researchers should critically assess potential biases or gaps inherent in specific datasets when conducting causality analysis.

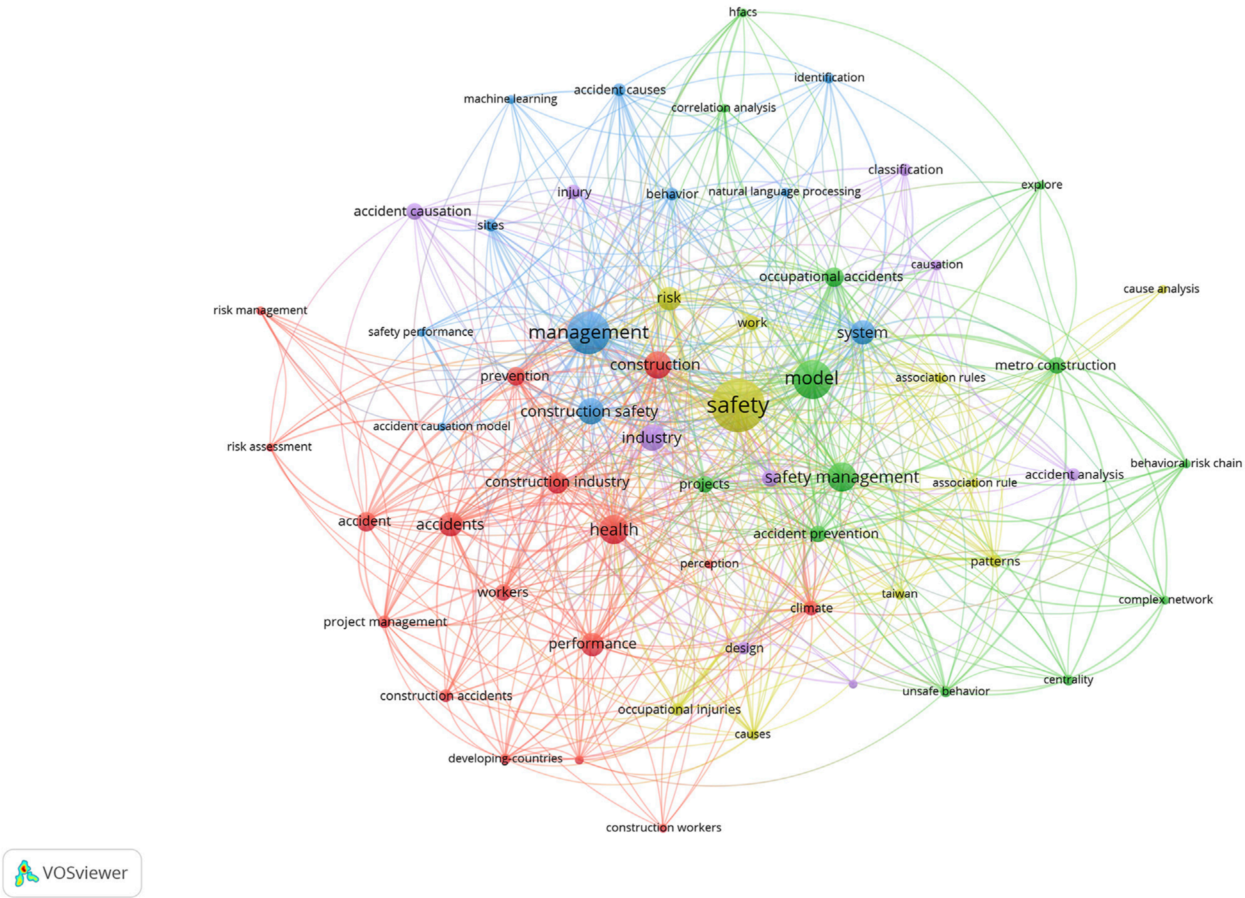

FIGURE 7
Co-occurrence network for keywords.

4.2 Identification and extraction of construction accident causality factors

Risk factor identification is recognized as the foundational step in safety risk management, essential for assessing risk levels and formulating mitigation strategies (Gul and Ak, 2018). Common accident causes in construction are pinpointed to guide safety practitioners in prioritizing preventive measures across project stages (Carrillo-Castrillo et al., 2017). Causality factors are analyzed scientifically to manage project risks effectively, ensure safety, enhance worker wellbeing, and support sustainable industry development, while also improving enterprise competitiveness and resilience against future risks.

4.2.1 Traditional methods

Various research methods for data collection, accident pattern analysis, and causality extraction are employed, each with distinct advantages and limitations. Multiple approaches are often combined to enhance result reliability and comprehensiveness. Traditional methods—surveys, literature reviews, expert interviews, site inspections, and causality extraction from existing data and case studies—are systematically reviewed, with specific steps, limitations, and supporting literature outlined in Table 6 to serve as a reference for future research. As shown in the table, traditional methods for identifying construction accident causation factors exhibit a trade-off between depth of insight and data generalizability. While expert-based and site-specific approaches (e.g., interviews, field investigations) offer detailed and contextualized knowledge, they often suffer from subjectivity and limited coverage. Conversely, methods relying on existing literature or institutional data allow for broader pattern recognition but may be constrained by data quality or research bias.

4.2.2 Advanced analysis and modeling methods

Advancements in technology and data processing have led to the adoption of sophisticated methods in construction accident causal analysis. Digital tools enable risk factor extraction from unstructured reports (Liu et al., 2024). Techniques such as natural language processing (NLP), deep learning, and statistical modeling, alongside complex system analysis, are utilized to deepen causal insights. NLP and machine learning models (e.g., KeyBERT, BERT) paired with clustering techniques extract key factors from extensive accident reports (Liu et al., 2024), while text mining reveals accident patterns in large datasets (Shen et al., 2024; Luo et al., 2021). Novel NLP, dimensionality reduction, clustering, and large language model (LLM) prompts are integrated to identify accident types and causes

TABLE 5 International data sources and institutions for construction safety.

Region	Institution name	Region	Institution name
China	Ministry of Emergency Management	Malaysia	Department of Occupational Safety and Health
China	State Administration of Work Safety	Australia	National Coronial Information System
China	Ministry of Housing and Urban-Rural Development	Greece	Greek Work Inspection Organization
China	Safety Management Network	Norway	Labour Inspection Authority
Hong Kong	Labour Department	Kuwait	Kuwait Municipality
Hong Kong	Occupational Safety and Health Council	Kuwait	Ministry of Social Affairs and Labor
Hong Kong	Coroner's Court	Israel	National Insurance Institute
Taiwan	Council of Labor Affairs	Israel	Statistical Abstracts of Israel
United States	National Institute for Occupational Safety and Health	India	New Delhi Television Limited
United States	Occupational Safety and Health Administration	Sweden	Swedish Social Insurance Agency
United States	Bureau of Labor Statistics	Sweden	Swedish Work Environment Authority
United States	Michigan Department of Transportation	Sweden	Statistics Sweden
United Kingdom	Health and Safety Executive	Morocco	Haut-Commissariat au Plan
South Korea	Construction Safety Management Integrated Information	Spain	Junta de Andalucía
South Korea	Korea Occupational Safety and Health Agency	Spain	Official Workplace Incident Notification Forms
South Korea	Ministry of Land, Infrastructure and Transport	Europe	European Statistics on Accidents at Work

(Smetana et al., 2024). Probabilistic models like HFACS, refined with qualitative comparative analysis, and the modified loss causal model establish causal chains and relationships (Li and Wen, 2022; Wang et al., 2022b; Chan et al., 2022). Deep learning approaches, such as the HANN model (Zhang, 2022), handle nonlinear modeling of complex datasets, while system models like ConAC and the Constraint-Response Model uncover intrinsic accident mechanisms (Winge et al., 2019; Behm and Schneller, 2013; Suraji et al., 2001). Fault tree analysis (FTA) combined with Boolean algebra and case studies further refines causal factor identification (Chi et al., 2014). These advanced methods surpass traditional approaches in depth and applicability, with ongoing technological progress promising enhanced accuracy and a stronger foundation for safety management.

4.2.3 Comprehensive analysis

Traditional methods, such as surveys, literature reviews, and expert interviews, are valuable for identifying accident causality factors but often face limitations in terms of accuracy and generalizability due to small sample sizes and subjectivity. These methods are typically more interpretable, providing direct insights, but they may overlook underlying patterns that advanced techniques can uncover. In contrast, advanced methods such as natural language processing (NLP) and deep learning offer enhanced accuracy by analyzing large datasets and identifying complex causal relationships. However, these methods often lack transparency, making it difficult for practitioners to fully understand the rationale behind the results. While traditional methods remain crucial for site-specific analysis and expert judgment, advanced methods are increasingly relevant as they enable more comprehensive, data-driven insights. The integration of both approaches can provide a more robust and effective framework for construction accident prevention.

4.3 Classification of construction accident types

Diverse and frequent construction safety accidents arise from complex risk factors (Shen et al., 2024). Accident type analysis is deemed critical for improving safety management (Smetana et al., 2024). Various classification methods proposed by scholars and institutions globally are reviewed to elucidate accident mechanisms and inform targeted safety recommendations (Zheng et al., 2018). Accidents are classified to aid prevention, emergency response, and the development of industry standards and safety technologies. Classification methods and accident type distributions across construction sectors and countries are examined, providing theoretical support for strengthening safety management practices.

TABLE 6 Traditional methods for causality factor identification.

Methods	Specific steps	Limitations	Literature
Questionnaire survey	Gather data via targeted questionnaires from professionals and experts to pinpoint key risk factors	Subjectivity risks bias; sample representativeness and poor design may compromise data quality	Antoniou and Merkouri (2021), Douglas and Adeloye (2016), Ali et al. (2024), Elsebaei et al. (2021), Techera et al. (2019), Leung et al. (2016), Rowlinson and Jia (2015), Chen et al. (2011)
Literature review	Search and synthesize existing studies to refine risk factors and identify hotspots	Depends on prior research; gaps, biases, outdated data, or method heterogeneity may skew results	Yang et al. (2024), Antoniou and Merkouri (2021), Douglas and Adeloye (2016), Elsebaei et al. (2021), Chen et al. (2011), Shen et al. (2024), Jiang et al. (2022), Pan et al. (2024), Feng (2023), Antoniou and Agrafioti (2023), Tong et al. (2021), Yap et al. (2020), Moosa et al. (2020), Pichugin and Dmytrenko (2018), Tarik and Adil (2018), Yilmaz (2015), Mohandes et al. (2022a), Belayutham et al. (2016), Mohandes et al. (2022b)
Expert interviews	Interview safety experts and managers to extract insights and potential accident causes	Subjective views and small sample size may overlook some risk factors	Rowlinson and Jia (2015), Chen et al. (2011), Tong et al. (2021), Belayutham et al. (2016), Mohandes et al. (2022b), Deng et al. (2024), Rafindadi et al. (2023), Fonseca et al. (2012), Kartam and Bouz (1998), Pekkarinen and Anttonen (1989)
Field investigation	Inspect sites to observe and record hazards in environment, equipment, and behaviors	Limited by time, resources, and scope; findings may not generalize industry-wide	Douglas and Adeloye (2016), Rowlinson and Jia (2015), Fonseca et al. (2012), Pekkarinen and Anttonen (1989), He et al. (2024)
Causation extraction based on existing data and cases	Analyze safety data and accident reports from agencies and institutes to extract causes and patterns	Constrained by data availability, quality, and integrity; case-specificity may limit generality	Zakaria et al. (2023), Chen N. et al. (2022), Betsis et al. (2019), Douglas and Adeloye (2016), Shen et al. (2024), Pan et al. (2024), Tong et al. (2021), Pichugin and Dmytrenko (2018), Yilmaz (2015), Rafindadi et al. (2023), Fonseca et al. (2012), Wu and Sun (2024), Chen et al. (2023), Chellappa (2022), Guo et al. (2021), Berglund et al. (2021), Jeong et al. (2022), Zhang W. et al. (2020), Zheng et al. (2018), Eteifa and El-adaway (2018), Gharaie et al. (2015), Chen et al. (2024), Chen F. et al. (2022), Nowobilski and Hoła (2023), Jabbari and Ghorbani (2016), Ma and Chen (2024), Choe and Leite (2020), Chi and Han (2013), Pines et al. (1987), Grant and Hinze (2013)

4.3.1 Analysis of construction accident types

Classification methods for construction accidents are predominantly based on multiple dimensions, such as direct causes, physical manifestations, and regional factors. Accidents are attributed to human unsafe behaviors, unsafe object conditions, environmental factors, and management deficiencies (Shen et al., 2024), or categorized by manifestations like falls from heights, object strikes, and collapses (Yang et al., 2024). With construction companies increasingly operating internationally, heightened safety risks and uncertainties are encountered (Jin et al., 2021). Risks in global projects stem from countries, partners, companies, and project-specific factors (Zhu et al., 2022), with Heinrich's theory applied to classify accidents into traditional and non-traditional safety risks, environment- and health-related incidents, and socio-cultural conflicts, aiding cross-cultural safety management (Jin et al., 2021). Regional studies highlight distinct risk profiles, offering valuable insights for multinational projects. Innovative classifications, such as work area intersections (high-altitude,

TABLE 7 Specific classification of major accident types.

Accident type	Specific description
Falling from heights	Workers fall from high places due to insufficient safety protection or improper operation
Object striking	Materials, tools, or equipment fall or are collided with due to poor management or operational mistakes
Collapse	Due to unstable foundations, unstable supporting structures, or construction quality issues, soil, formwork, scaffolding, etc., collapse, potentially leading to the collapse of the entire building
Electric shock	Workers come into contact with live electrical components due to equipment malfunction, poor maintenance, or operational errors
Fire and explosion	Fires or explosions are triggered on the construction site due to flammable materials, gases, or improper operations
Compression/collision	Improper equipment operation or material handling causes workers to be compressed or struck by machinery or heavy objects
Hit by falling objects	Materials or tools fall from heights during hoisting and installation, striking workers
Traffic-related accidents	Improper vehicle operation or poor traffic management on the construction site leads to workers being hit or run over by vehicles
Chemical exposure	Workers are exposed to harmful chemicals or toxic gases, resulting in poisoning or health issues
Extreme temperature exposure	Workers work in high or low-temperature environments without protective measures, potentially leading to heatstroke or frostbite

ground, or combined cross-working) (Chen et al., 2023) and severity levels (general, major, serious, particularly serious) (Chen N. et al., 2022), refine risk characterization, noting that falls, collapses, strikes, and lifting injuries dominate (~80% of incidents). Additional categories—entrapment, electrocution, chemical exposure, temperature extremes, fires, explosions, and traffic accidents—are also recognized (Zhang J. et al., 2020). Advanced tools like graph neural networks are employed to classify unstructured reports efficiently (Pan et al., 2022), while the Task-Competence-Interaction model links accident risk to mismatches between task demands and worker capabilities (Kartam and Bouz, 1998). These multidimensional approaches, evolving toward standardization and dynamism, provide robust theoretical support for safety management, with future efforts urged to align classification with practical safety enhancements.

4.3.2 Summary of construction accident types

Accident type frequency and proportion in construction vary by research perspective and data source. Falls from heights, object strikes, and collapses consistently predominate, with falls leading across studies (Zakaria et al., 2023; Betsis et al., 2019; Jabbari and Ghorbani, 2016), while electrocution, fires, and explosions, though less frequent, remain significant risks (Rafindadi et al., 2023; Hwang et al., 2023). These patterns inform targeted safety measures. Common accident types are refined based on physical manifestations and prior research, as detailed in Table 7. Scientific classification underpins safety management by linking accident types to specific work environments, operational methods, and management factors, enabling precise prevention strategies. Major categories—falls, strikes, collapses, electrical shocks, and fires/explosions—alongside specific incidents like falling object strikes, traffic accidents, chemical exposure, and temperature extremes, are delineated to enhance risk assessment and training. Future refinements, integrating dynamic analysis and modern technology with occurrence data, are expected to bolster safety management guidance.

4.4 Causal factor correlation analysis methods and applications

Causal factors are recognized to potentially trigger one another, ultimately leading to accidents (Yang et al., 2024). Understanding these mechanisms is deemed essential for accident prevention, enhancing construction management and technical capabilities (Qie and Yan, 2022). Causal factors and their interrelationships are analyzed from four perspectives—traditional statistical, advanced statistical, network- and structure-based, and advanced data analysis methods—to identify key factors and construct accident chains, thereby supporting risk control, industry safety, and sustainable development.

4.4.1 Traditional statistical analysis methods

Traditional statistical methods are employed as foundational tools for identifying accident causes and exploring simple relationships in construction accident analysis. Their limitations in addressing complex causal interactions are acknowledged, as detailed in Table 8. Combining these with advanced techniques is recommended to achieve more comprehensive insights. This table highlights the complementary nature of traditional statistical methods in causation analysis. Descriptive statistics provide an accessible overview of factor distributions, while correlation analysis enables deeper exploration of pairwise relationships. Meta-analysis serves to integrate findings across studies but may obscure contextual variability. Together, these methods offer a layered understanding of causation patterns, though each carries limitations in handling complex or multifactorial interactions.

TABLE 8 Traditional methods for causal correlation analysis.

Method	Advantages	Limitations	Applications
Descriptive statistical analysis	Simple, intuitive; reveals basic cause distribution	Struggles with complex causal relationships	Rank and identify key factors using mean, median, mode, frequency, variance, SD, and RII (Ali et al., 2024; Elsebaei et al., 2021; Yap et al., 2020; Chi and Han, 2013); Apply descriptive statistical methods (Pekkarinen and Anttonen, 1989; Oni et al., 2024)
Correlation analysis	Quantifies linear/nonlinear factor relationships	Limited to pairwise analysis; weak on multi-factor interactions	Explore factor relationships using Chi-square, Phi, lambda, Kendall, Pearson, and Spearman (Zakaria et al., 2023; Alomari et al., 2020; Betsis et al., 2019; Leung et al., 2016; Zheng et al., 2018; Chi and Han, 2013; Li and Wen, 2022; Chi et al., 2009; Li and Xiang, 2011); Examine cause-consequence links (Nowobilski and Hoła, 2023; Behm and Schneller, 2013; Fung and Tam, 2013); Analyze categorical variable correlations via contingency tables (Carrillo-Castrillo et al., 2017); Identify key causes with GRA (Zhang W. et al., 2020)
Statistical meta-analysis	Synthesizes multiple studies; evaluates common factors	Ignores study-specific nuances; sensitive to data quality	Assess common factor importance across studies (Antoniou and Agrafioti, 2023)

4.4.2 Advanced statistical analysis methods

Advanced statistical methods are increasingly applied to uncover risk factors and their interrelationships in construction accident causation, enabling the development of robust analysis models for improved prevention and management accuracy. Challenges related to applicability, data needs, and computational complexity are outlined in Table 9. The table reflects a growing tendency toward the use of more sophisticated analytical techniques in causation studies. These approaches offer expanded capabilities for exploring hidden patterns, complex relationships, and uncertainty within the data. While they hold promise for producing more nuanced insights, their effective application often hinges on appropriate methodological design and data conditions.

4.4.3 Network and structure-based analysis methods

Network- and structure-based methods are utilized to reveal complex factor interactions, pinpoint key elements, and trace influence pathways in construction accident analysis. Their strengths in managing complex systems and dynamic interactions are highlighted, though high demands on network construction, data quality, and computation are noted in Table 10.

4.4.4 Advanced data analysis methods

With digital technology advancements, advanced data analysis methods are leveraged to process large-scale data and uncover intricate relationships in construction accident causation through sophisticated algorithms. These methods support accident prevention by identifying underlying patterns, yet face challenges such as limited interpretability, high costs, and reliance on specialized expertise, as presented in Table 11. The table illustrates a gradual shift toward structural and network-based thinking in causation analysis. These methods help to represent complex interdependencies and visualize cause-effect linkages in more systematic ways. Although promising in theory and structure, their effective use still relies on suitable data inputs and careful model interpretation.

4.4.5 Comprehensive analysis

Traditional statistical methods offer strong interpretability and ease of use but struggle to capture the multifactorial and nonlinear relationships often present in construction accidents. In contrast, advanced statistical and network-based approaches demonstrate superior accuracy and structural insight, yet they typically require large datasets and involve complex modeling processes, limiting their practical applicability. Advanced data-driven techniques—such as machine learning and deep learning—excel at handling large-scale data and detecting hidden patterns, but often suffer from limited transparency and high computational and expertise demands. Therefore, a trade-off exists between interpretability and analytical capability across different methods. To address this gap, an integrated analytical framework combining traditional, advanced statistical, and data-driven methods can be adopted. This approach enhances the robustness and comprehensiveness of causal factor analysis by leveraging the strengths of each method, ensuring more accurate and holistic insights into construction accident causation. Collaborative approaches, such as combining statistical and machine learning techniques (Rafindadi et al., 2023; Li and Wen, 2022; Nguyen et al., 2024) or Bayesian networks with SNA,

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TABLE 9 Advanced methods for causal correlation analysis.

Method	Advantages	Limitations	Application
Structural equation modeling	Analyzes multiple causal relationships; handles latent variables	Needs large samples; relies on strict assumptions	Identifies key risk factors and their interrelationships (Feng, 2023; Jin et al., 2021; Oni et al., 2024; Li and Xiang, 2011)
Multiple linear regression	Builds causal models; quantifies factor contributions	Weak on non-linear relationships; demands high-quality data (e.g., normality)	Selects significant accident predictors via stepwise regression (Leung et al., 2016). Explores links between causality theory and prevention (Fung and Tam, 2013)
Cluster analysis	Uncovers data structures; adaptable; manages large datasets	Sensitive to parameters; affected by data distribution; struggles with high dimensions	Groups data by similarity using K-means (Smetana et al., 2024). Categorizes data into 5 cause-based clusters (Nowobilski and Hoła, 2019)
Grey relational analysis	Detects factor relationships under uncertainty	Requires normalization; sensitive to model choice and data quality	Identifies key accident causes (Zhang W. et al., 2020)

TABLE 10 Network-based methods for causal correlation analysis.

Method	Advantages	Limitations	Applications
Social network analysis (SNA)	Visualizes complex factor relationships; identifies key nodes and paths	Relies on expert knowledge and data quality; metrics lack expert interpretation	Models causes as nodes and relationships as edges, analyzing connection strength via adjacency matrix (Pan et al., 2024; Eteifa and El-adaway, 2018; Nguyen et al., 2024)
Complex network analysis	Uncovers dynamic factor interactions and propagation paths	High computational complexity; needs large data; limited dynamic adaptability	Builds behavior risk chain networks, analyzing attributes like degree and centrality (Yang et al., 2024; Deng et al., 2024; Guo et al., 2021; Hwang et al., 2023; Tang et al., 2022; Guo et al., 2020)
Bayesian network (BN)	Manages uncertainty and complex causal relationships probabilistically	Lacks expert-guided structure; demands complete data and high computation	Uses Copula BNs for probability distributions and risk propagation (Chen et al., 2024). Identifies key factors via reasoning and sensitivity analysis (Qie and Yan, 2022)
Analytic hierarchy process	Simplifies complex decisions; easy to use	Subjective; needs consistent data; weak on large-scale issues	Prioritizes accident factors (Kim et al., 2020; Vosoughi et al., 2020; Rafindadi et al., 2022)
Causal chain analysis	Clarifies causal relationships; aids system understanding	Subjective; expert-dependent; hard to quantify; poor dynamic fit	Represents event relationships through causal chains (Mohandes et al., 2022a; Belayutham et al., 2016; Mohandes et al., 2022b; Rafindadi et al., 2023; He et al., 2024; Wu and Sun, 2024; Chen et al., 2024; Chen F. et al., 2022; Ma and Chen, 2024; Behm and Schneller, 2013; Suraji et al., 2001; Li et al., 2024; Mitropoulos et al., 2005)
FTA	Systematically traces failure causes; supports risk assessment	Complex to build; data-intensive; limited dynamic reflection	Identifies key causes with Boolean algebra and MCS (Chi et al., 2014). Analyzes metro accident mechanisms (Qie and Yan, 2022)

TABLE 11 Data-driven methods for causal correlation analysis.

Method	Advantages	Limitations	Applications
Association rule mining (ARM)	Uncovers key factor associations from large datasets	Sensitive to sparse data; many rules reduce interpretability	Identifies factor associations using Apriori and FP-Growth based on support, confidence, lift (Chen N. et al., 2022; Tong et al., 2021; Rafindadi et al., 2023; Chen et al., 2023; Luo et al., 2021; Li and Wen, 2022; Nguyen et al., 2024; Yoon et al., 2024; Guo et al., 2022)
Naive bayes network (NBN) and tree-augmented naive bayes network (TAN)	Effective for classification; accounts for factor interactions	Assumes independence; needs specific data distribution	Analyzes factor-accident type links and identifies risks with NBN and TAN (Shen et al., 2024). Performs risk factor and coupling analysis (Liu et al., 2024)
Dynamic bayesian network	Handles dynamic and time-series data	High computational demand; requires complete data	Ranks risk factors and assesses criticality via sensitivity analysis (Jiang et al., 2022)
Text mining and machine learning	Processes large text data; extracts key insights	Needs extensive preprocessing; limited interpretability	Weights keywords with TF-IDF (Luo et al., 2021). Clusters accidents using K-means and t-SNE with LLM (Smetana et al., 2024). Extracts keywords via TextRank (Pan et al., 2022). Analyzes models with knowledge graphs (Li et al., 2024)
Deep learning methods	Manages large, complex datasets	Demands quality labeling; complex training/tuning	Reveals accident-injury relationships using GCN and co-occurrence networks (Pan et al., 2022)

are adopted to enhance accuracy and model propagation paths, despite challenges like computational demands and integration barriers. Methods or combinations are selected based on research goals, data traits, and resources to yield precise, comprehensive causation insights.

4.5 The application of artificial intelligence and large models and future prospects

4.5.1 Application progress of artificial intelligence and large models

Emerging technologies, including big data, artificial intelligence (AI), and the Internet of Things (IoT), are harnessed to support real-time monitoring, accident prevention, and causal analysis in construction, significantly enhancing safety management (Deng et al., 2024). AI and large models are increasingly applied to identify risk factors, analyze causal relationships, and predict risks, offering intelligent, data-driven solutions. Text mining combined with Bayesian networks extracts risk factors from reports using algorithms like TF-IDF and TextRank, with improved Bayesian models identifying key factors despite limitations in semantic and temporal dynamics (Shen et al., 2024). Dynamic Bayesian networks and N-K models are utilized to assess risk coupling in deep excavation near tunnels, aiding on-site safety decisions (Jiang et al., 2022). Metro accident causality networks, built via data mining and network theory, reveal topological links between accidents and factors, optimizing safety resource allocation (Deng et al., 2024). The BERT and TAN model achieves high performance (AUC 0.938) in risk factor extraction (Liu et al., 2024), while GPT-3.5, paired with NLP and clustering, analyzes OSHA data for real-time safety advancements (Smetana et al., 2024). ARM uncovers risk factor combinations—e.g., management, site conditions, and behavior in Malaysia (Rafindadi et al., 2023)—and patterns in cross-operations (Chen et al., 2023) and fall accidents (Luo et al., 2021). Text classification and causal modeling are advanced through Word2Vec and hybrid neural networks (Zhang, 2022), convolutional bidirectional LSTM (C-BiLSTM) for OSHA narratives (Antoniou and Merkouri, 2021), Copula Bayesian networks for collapse accidents (Chen et al., 2024), and NLP with Accimap for systematic risk analysis (Ma and Chen, 2024). Fault tree analysis with Bayesian networks dynamically assesses subway accident risks (Qie and Yan, 2022), and contextual semantic networks (CCNet) enhance classification using deep learning and attention mechanisms (Gupta et al., 2022). Tunnel accident databases highlight geological unpredictability (Sousa and Einstein, 2021), while knowledge graphs integrated with BIM identify high-risk factors like unsafe behavior and poor management (Li et al., 2024). Python-based processing of complex data aligns with deep learning for future intelligent systems (Nowobilski and Hoła, 2023). These technologies collectively bolster analysis efficiency, accuracy, and decision-making in construction accident causation.

4.5.2 The limitations of artificial intelligence and large models and future prospects

While the AI models mentioned show potential in risk factor identification and accident causation analysis, their effectiveness,

TABLE 12 Limitations of AI-Based approaches in current research.

Literature	Research aspect	Specific issues
Rafindadi et al. (2023), Chen et al. (2024), Nowobilski and Hoła (2023)	Data	Small sample size, limited to a specific region, not globally representative
Luo et al. (2021)	Data	Incomplete accident causation dictionary, large time span in data samples
Zhang (2022)	Model	Deep neural network has low time efficiency
Zhang J. et al. (2020)	Model	C-BiLSTM model requires manual data labeling, which has limitations
Liu et al. (2024)	Model	Lack of precise threshold for feature dimensions, model performance needs improvement
Gupta et al. (2022)	Model	CCNet model lacks explanation of internal mechanisms
Shen et al. (2024)	Methodology	Deficiencies in semantic associations and dynamic time changes
Ma and Chen (2024)	Methodology	Only combined unsupervised NLP and Accimap, failing to utilize other advanced techniques
Luo et al. (2021)	Methodology	Insufficient construction of accident causation dictionary and sample selection, resulting in the absence of time characteristics in causation identification

scalability, and feasibility in real-world applications require further evaluation. Practical implementation depends on data quality, model adaptability, and integration with existing safety management systems. Validation in real-world projects is essential to ensure accuracy and reliability. Scalability remains a concern, especially in resource-limited smaller projects. A comprehensive evaluation of model performance is crucial for optimizing their broader application.

Limitations in data, models, and methods are encountered in current research, as detailed in Table 12. Advances in AI, large models, and data mining offer new opportunities for construction accident causation analysis. Future research directions, outlined in Table 13, emphasize improving risk identification accuracy and intelligence. The integration of these technologies is poised to deliver precise, efficient solutions, though ongoing efforts in data quality, model optimization, and interpretability are required to ensure practical, scalable outcomes for construction safety management. Particularly, the challenges related to data quality, such as incomplete or biased datasets, can significantly impact model performance and generalization across diverse construction contexts.

In addition to technological advancements, it is crucial to consider the ethical and policy implications of AI-based accident prediction models. Issues such as data privacy, algorithmic fairness, and transparency in decision-making should be carefully addressed to ensure that these models are used responsibly and effectively in construction safety management. Furthermore, policy frameworks may need to be updated to support the integration of AI in safety protocols, ensuring that the models are aligned with industry standards and regulatory requirements.

5 Conclusion

This review offers a comprehensive understanding of the evolving landscape of construction accident causation research, highlighting a transition from traditional qualitative approaches to data-driven, intelligent methodologies. Beyond identifying key hotspots and influential networks, the findings underscore a broader epistemological shift: the integration of advanced computational techniques—such as AI, large models, and graph-based learning—is reshaping how causality is conceptualized, modeled, and predicted in the construction domain.

The contributions of this study are outlined as follows. First, it highlights certain gaps in the bibliometric application to building accident causation analysis, with an effort to identify key research hotspots, academic collaboration networks, and high-impact literature. This process has resulted in a knowledge map that may serve as a useful reference for future investigations. Second, a conceptual approach is introduced, combining bibliometric and qualitative analysis. Quantitative data are used to inform content interpretation, offering a more systematic understanding of the evolution of research methods in building accident causation analysis. Rather than focusing on single-method analyses, the study emphasizes the development of research approaches over time and how these methods have influenced the identification of key risk factors and their interrelationships. Additionally, the study examines the role of emerging technologies, such as artificial intelligence and large-scale models, in building accident causation analysis, offering insights into their potential integration into intelligent safety management practices.

Despite the systematic review of the research status of building accident causation analysis and the proposal of future development

TABLE 13 Prospective developments in AI and large model research.

Future work	Key technologies	Research focus	Literature
Deep semantic understanding and dynamic modeling	NLP, transformer/LSTM time series analysis, large models (GPT-4, T5)	Deeply mine implicit semantic information in accident report texts; enhance dynamic tracking and evolution prediction of risk factors	Liu et al. (2024)
Multi-level risk network construction and knowledge graph integration	Big data analysis, association rule mining, bayesian networks, knowledge graphs	Construct cross-dimensional, multi-level accident causation networks; integrate structured and unstructured data; enhance interpretability of causality analysis	Shen et al. (2024), Nowobilski and Hoła (2023), Li et al. (2024)
Multi-modal data fusion and intelligent warning systems	IoT, deep learning, reinforcement learning, big data platforms, web crawling	Fusion analysis of multi-source heterogeneous data (text/image/sensor); real-time dynamic monitoring & adaptive warning	Ma and Chen (2024), Li et al. (2024), Gupta et al. (2022)
Dataset expansion and model generalization improvement	Standardized accident database construction, data crawling and structuring, ensemble learning	Build standardized accident databases across regions and scenarios; address data imbalance issues; improve model generalization and cross-platform applicability	Rafindadi et al. (2023), Ma and Chen (2024), Li et al. (2024)

directions, certain limitations persist. First, the bibliometric analysis is primarily based on the Scopus and Web of Science databases with specific search terms, which may exclude some relevant literature, industry reports, government documents, and studies published in Chinese. This limitation potentially compromises the comprehensiveness and representativeness of the findings. To mitigate this, future research could expand the scope of literature sources by incorporating additional databases, such as Google Scholar, and including grey literature, such as industry reports and government publications. Furthermore, studies could be expanded to non-English sources to ensure a more comprehensive understanding of the global research landscape. Second, while bibliometric methods effectively highlight research hotspots and collaboration networks, their capacity to deeply probe accident causation remains limited. To address this, future studies could incorporate causal inference and complex system modeling to strengthen the explanatory power and causal reasoning of the analysis. Moreover, the reliance on bibliometrics and qualitative analysis in this study precludes specific quantitative empirical validation of the practical effectiveness of various technologies in building accident causation analysis. To mitigate this limitation, future research could conduct empirical studies using real-world accident data to evaluate the effectiveness of emerging technologies like AI and large-scale models in practical applications. From a research perspective, emphasis is placed on methodological approaches to building accident causation analysis, particularly technical methods, while non-technical factors—such as policies, regulations, and organizational management—are not considered. Future research could expand to include these non-technical dimensions to enrich the depth and scope of building accident causation analysis.

Future investigations should further examine the application potential of large-scale models in construction safety management, foster interdisciplinary collaboration, and develop intelligent, precise accident prevention systems. Specific areas warranting attention include the following: first, data quality improvement through the establishment of standardized accident databases across regions and scenarios, mitigation of data imbalance, and enhancement of model generalization and cross-platform applicability; second, reinforcement of model interpretability to ensure transparency and traceability of analysis outcomes, thereby providing dependable support for practical safety management; third, advancement of interdisciplinary integration by combining technologies such as the IoT, big data, and reinforcement learning to create multimodal data fusion and intelligent early warning systems, enabling the analysis of multi-source heterogeneous data and real-time dynamic monitoring. For instance, a partnership between construction engineers, data scientists, and psychologists could lead to the development of advanced machine learning models that integrate behavioral data, environmental factors, and real-time site conditions to predict and mitigate human errors in construction activities. Such collaboration could result in the creation of a predictive framework that considers cognitive load, stress levels, and safety perceptions alongside traditional environmental factors, ultimately improving accident prevention strategies.

With ongoing technological progress and deeper exploration, building accident causation analysis is anticipated to yield smarter safety management solutions for the construction industry, facilitating progress toward higher quality, enhanced safety, and more sustainable development.

Author contributions

HZ: Funding acquisition, Visualization, Formal Analysis, Validation, Supervision, Data curation, Writing – review and editing, Methodology, Writing – original draft, Conceptualization. ML: Formal Analysis, Writing – review and editing, Methodology, Writing – original draft, Conceptualization, Visualization. ZJ: Formal Analysis, Writing – original draft, Resources, Methodology, Conceptualization, Writing – review and editing. JH: Writing – original draft, Methodology, Formal Analysis, Conceptualization, Writing – review and editing, Resources.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This research was funded by Shandong Province Natural Science Foundation, grant number ZR2023QG168.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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