

Review

A Science Mapping Approach-Based Review of Construction Workers' Safety-Related Behavior

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Abstract: Promoting safe behaviors among construction workers and mitigating unsafe behaviors is an effective approach to enhancing safety performance in the construction industry. Although progress has been made, the research themes concerning construction workers' safety-related behaviors (CWSRB) and the detailed progress of each theme remain unclear due to differences in review perspectives and conceptual scopes. This study utilized CiteSpace software (V6.2R3 version) to conduct an analysis of co-authorship networks, co-word networks, and co-citations on 563 published articles in this field from 2013 to 2023. This study's outcomes highlight several key insights: (1) journals such as *Safety Science* play a pivotal role in the domain; (2) institutions such as the City University of Hong Kong and Hong Kong Polytechnic University, along with prolific authors like Li, are major contributors to the field; (3) the focus of research has evolved from early organizational factors towards a more diverse range of topics, with deep learning emerging as a significant current research hotspot; (4) this study has identified high-cited literature and 11 primary clusters within the field. Current research focuses on five areas: safety-related behavior concepts, influencing factors and consequences, formation mechanisms, interventions, and applications of new technologies. Establishing clear classification criteria for unsafe behaviors, comprehensively understanding the formation mechanisms of safety-related behaviors, evaluating the effectiveness of intervention strategies, and exploring the practical applications of new technologies are future research directions. This study provides researchers with a holistic view of the present state of research and potential avenues for future exploration, thereby deepening the knowledge and comprehension of stakeholders within this domain.

Keywords: construction workers; safety-related behaviors; CiteSpace; content analysis



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1. Introduction

The construction industry exhibits a mortality rate that is significantly higher than in other sectors [1,2]. Despite considerable efforts, safety issues in the construction industry remain severe. According to data released by China's Ministry of Housing and Urban-Rural Development, there were as many as 3817 deaths in housing and municipal engineering safety accidents in the past five years [3]. In the United States, while the Bureau of Labor Statistics reported a slight decline, the number of fatalities on construction sites in 2021 still reached 986 [4]. Similarly, the state of construction safety in countries and regions such as South Korea, Spain, and Australia is concerning [5,6]. Globally, persistent safety concerns within the construction industry underscore its status as a formidable challenge. Among the manifold causes of safety incidents, unsafe behaviors among construction workers emerge as the key factor [7–9]. An analysis of 500 safety incidents in the construction industry has revealed that over 70% of accidents are attributed to unsafe behaviors [8].

Promoting safe behaviors among construction workers and mitigating unsafe behaviors is an effective approach to enhancing safety performance in the construction industry. Numerous studies have explored construction workers' safety-related behaviors (CWSRB), examining correlations between unsafe behaviors and accidents [10,11], factors influencing safe and unsafe behaviors [12–15], mechanisms underlying the formation of safe and unsafe behaviors [16–20], the identification and supervision of unsafe behaviors [21,22], and interventions targeting unsafe behaviors [23,24]. Despite the wealth of research outcomes, existing findings still struggle to adequately elucidate the complex formation and development of safety-related behaviors on site. There is a need to clarify the directions for future research based on existing research.

Conducting a literature review is an expedient approach to gain a comprehensive understanding of a research domain [25]. In recent years, there has been significant progress through comprehensive reviews that adopt various perspectives. For example, Xia et al. [13] focused on the antecedents of construction workers' safe behaviors, while Hu et al. [26] and Xiang et al. [27] examined the cognitive mechanisms underlying unsafe behaviors from a cognitive science standpoint. While these focused reviews deepen our understanding within their respective areas, they may not fully capture the field's broader research landscape. Reviews from a broader perspective have yielded relevant outcomes. Meng et al. [28] have critiqued the mechanisms of unsafe behavior formation and intervention measures based on factor identification. Nonetheless, traditional review methods that rely on manual screening may have limited scope and are prone to subjective bias. Cheng et al. [29] introduced scientometric analyses, and their review—expanding the concept of safety-related behaviors—could further refine the selection of the review sample and delve deeper into specific research topics.

The existing literature reviews offer valuable insights into the dynamic nature of the research field. However, there remains a lack of detailed presentation on the progress of various research themes related to construction workers' safety production behaviors, which can adversely affect the understanding of current research advancements and the clarification of future research directions. To fill in the gaps, this study conducts a comprehensive and meticulous examination of the literature in the field by integrating scientometric analyses with textual content analysis. This work includes identifying influential journals, scholars, and research teams within the domain; extracting key terms to illustrate research hotspots and developments; recognizing significant references and visually presenting research categories through cluster analysis; and, building on this work, distilling the main research themes and summarizing progress through the textual content analysis of key studies, offering insights into directions for future research endeavors. The findings of this research can provide practitioners and researchers with a valuable reference for thoroughly understanding the current state of the domain and guide the direction of future research work.

2. Research Methodology

As a Java-based software for visualizing and analyzing literature, CiteSpace facilitates structured exploration of vast textual data using co-citation analysis and pathfinder network algorithms [30]. It reveals the structure, patterns, and distribution of disciplinary knowledge and generates visual knowledge maps, thereby exploring the research hotspots, frontiers, key authors, and institutions within a specific field of study. It is widely recognized as a foundational tool for literature review endeavors. In this study, leveraging the V6.2R3 version of CiteSpace, we aim to perform a multidimensional literature review encompassing co-authorship, co-word, and co-citation analyses. While CiteSpace software is capable of conducting frequency statistics and a structured overview of the domain, it has limitations in delving into the specifics of the study. Therefore, further content analysis is applied to the identified key studies to enhance the understanding of the research details. The amalgamation of quantitative and qualitative analysis results is intended to consolidate

prevailing research themes in CWSRB and chart potential trajectories for future research. The methodological approach is outlined in Figure 1.

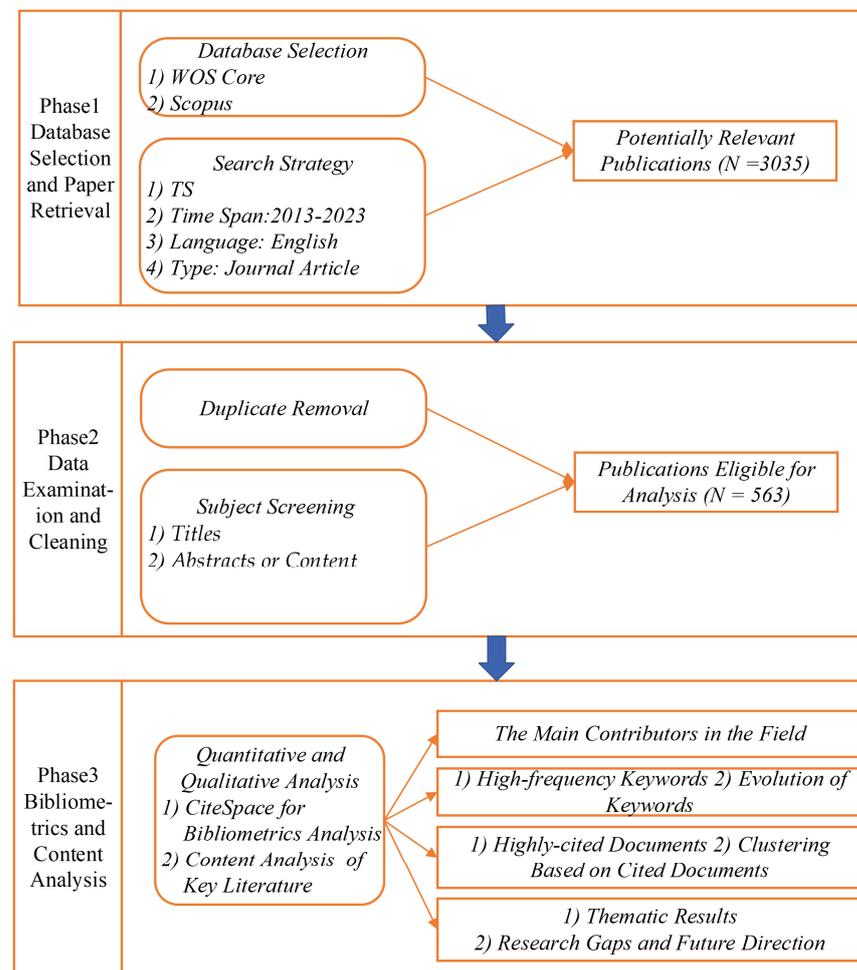


Figure 1. Research design.

2.1. Database Selection and Paper Retrieval

The relevant literature was sourced from articles indexed in the Web of Science Core and Scopus databases. These databases provide a comprehensive research scope within the target field and are frequently utilized by researchers in the construction domain for literature reviews [31,32].

To minimize the potential omission of target literature, this paper employs a thematic search approach, drawing on strategies from related review retrieval methods [21,33]. The search strategy is $TS = (\text{construction worker}^* \text{ or } \text{building worker}^* \text{ or } \text{construction employee}^*) \text{ AND } TS = (\text{*safety behavior}^* \text{ or } \text{*safety behaviour}^* \text{ or } \text{*safe behavior}^* \text{ or } \text{*safe behaviour}^* \text{ or } \text{*safety participation}^* \text{ or } \text{*safety performance}^* \text{ or } \text{*safety violation}^* \text{ or } \text{*unsafe act}^* \text{ or } \text{*unsafety act}^*)$. The asterisk (*) is used for fuzzy searching, and TS represents the literature theme, encompassing titles, abstracts, and keywords. Given the significant concentration of major research outcomes in the past decade, the search timeframe was set from 1 January 2013 to 31 December 2023. Only journal articles were included to ensure data quality, and the language was confined to English. This search yielded a total of 3035 literature entries, with 1636 from WOS and 1399 from Scopus.

2.2. Data Examination and Cleaning

To eliminate duplicates and ensure a comprehensive literature review, we imported the retrieved articles from two databases into EndNote 20, utilizing its de-duplication

feature. Initially, we set the de-duplication parameters to title, publication year, and author to automatically identify and remove duplicate records. Subsequently, we refined our process by focusing on the title alone, which enabled a detailed manual review of the remaining entries. Each potential duplicate was scrutinized individually to confirm its uniqueness. This meticulous approach led to the removal of all duplicate entries, culminating in a refined dataset of 1831 distinct papers for further analysis. A two-stage review process was conducted to maintain alignment with the study's focus on production-related behaviors among construction workers. Before the review, it was specifically stated that this study focuses on production-related behaviors among construction. In the first stage, studies unrelated to CWSRB were excluded by reading titles. For instance, the study by Dong et al. [34], which focused on the safe use of prescription opioids and non-opioid analgesics among American construction workers, fell outside the scope of the review and was therefore eliminated. A total of 616 literature entries were excluded in this stage.

In the second stage, the literature was carefully assessed for relevance to the research themes, with abstracts and full texts reviewed as needed. For instance, the research by Nnaji et al. [35], which investigated how safety and health measures by American construction companies influenced the spread of COVID-19, was excluded due to its non-specificity to construction workers' operational safe behaviors. This phase led to the exclusion of 652 entries.

Ultimately, a curated collection of 563 entries was selected, which was then analyzed to enhance understanding in the field of construction workers' safe behaviors.

3. Overview of Selected Publications on CWSRB

3.1. Trends in the Number of Publications

Figure 2 presents the annual distribution of the 563 selected publications, highlighting the research trajectory of CWSRB. Initially, with less than 20 publications in 2013 and 2014, CWSRB did not attract significant attention in safety management. However, a surge in interest is evident from 2015, with publications reaching 50 annually by 2018 and exceeding 100 by 2022. Due to the retrieval timeframe, some publications from 2023 may be unaccounted for. The growing focus on CWSRB, closely linked to safety incidents, is expected to continue amid ongoing challenges in construction safety, foreshadowing a rise in scholarly contributions to the field.

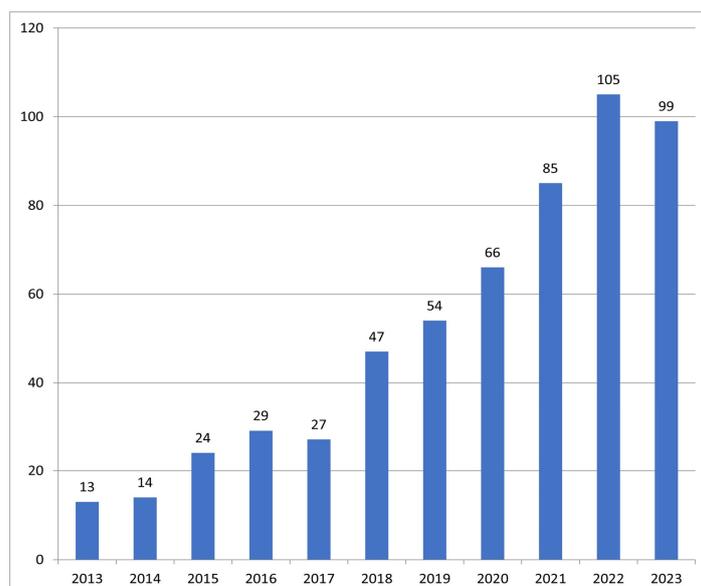


Figure 2. Annual publications of CWSRB from 2013 to 2023.

3.2. Journal Source Distribution

The 563 publications are distributed across 141 journals. Table 1 lists the journals with more than ten publications. The top twelve journals account for 340 publications, constituting 60% of the total. According to Bradford's law [36], these top thirteen journals can be considered the core journals in the field. Among them, *Safety Science*, the *Journal of Construction Engineering and Management*, and *Automation in Construction* collectively account for 32% of the total publications, playing a crucial role in CWSRB research.

Table 1. Major journals of 563 publications.

NO.	Journal	Count	Total Citations	Average Citations
1	<i>Safety Science</i>	70	419	6
2	<i>Journal of Construction Engineering and Management</i>	68	375	6
3	<i>Automation in Construction</i>	46	279	6
4	<i>International Journal of Environmental Research</i>	37	12	0
5	<i>Engineering Construction and Architectural Management</i>	32	123	4
6	<i>Sustainability</i>	20	85	4
7	<i>Advanced Engineering Informatics</i>	13	116	9
8	<i>Journal of Safety Research</i>	12	296	25
9	<i>Journal of Management in Engineering</i>	11	216	20
10	<i>Buildings</i>	11	26	2
11	<i>Frontiers in Psychology</i>	10	54	5
12	<i>Journal of Computing in Civil Engineering</i>	10	133	13

When examining both the total citations and the average citations per publication, it was observed that, despite relatively lower publication volumes, journals such as the "Journal of Management in Engineering" and the "Journal of Computing in Civil Engineering" exhibit higher average citation rates. This reflects the significant influence that these journals wield within the field.

4. Co-Author Analysis

Co-authorship analysis is an analysis based on the joint authorship of authors in a study. Co-author analysis aids in identifying key authors and understanding the collaborative relationships among them and provides a window into the research dynamics of the domain. The bibliographic data were imported into the CiteSpace software, with the time slice parameter set to 1 and the top nodes extracted for each time slice, to construct networks of countries/regions, institutions, and authors.

4.1. Analysis of Co-Country/Region and Co-Institution Networks

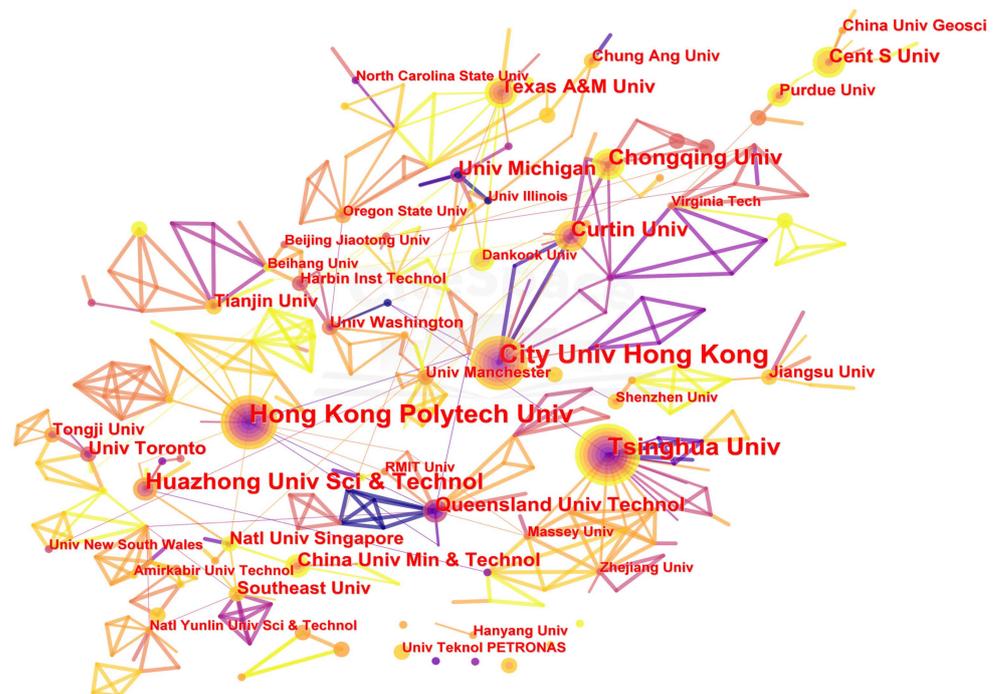
Table 2 presents detailed information on the top 10 countries/regions ranked by frequency and centrality. Although China and the United States ranked first and second in publication output, China's centrality was only 0.06, and the United States ranked eighth in centrality, reflecting their limitations in international collaboration. Despite having lower publication outputs, countries such as Italy, England, and Saudi Arabia played pivotal roles in international collaborations, significantly influencing the promotion of widespread cooperation within the field.

From the analysis of node details, it can be inferred that during the integration of information technology into CWSRB research, technologically advanced nations like the United States and Australia occupy a position as technology spillover sources, whereas China's rapid progress in this domain cannot be ignored.

Table 2. Top 10 countries/regions in frequency and centrality.

NO.	Countries/Regions (Frequency)	Countries/Regions (Centrality)
1	China (264)	Italy (0.73)
2	USA (115)	England (0.71)
3	Australia (77)	Saudi Arabia (0.68)
4	South Korea (41)	Spain (0.66)
5	England (23)	Australia (0.64)
6	Iran (23)	South Korea (0.6)
7	Malaysia (20)	Malaysia (0.49)
8	Canada (19)	USA (0.36)
9	Taiwan (19)	Nigeria (0.31)
10	Indonesia (11)	Taiwan (0.22)

This paper extracted the top 50 institutions to construct a collaboration network, as depicted in Figure 3. This network comprises 656 nodes and 818 links, illustrating the extensive focus of research institutions on CWSRB. However, based on frequency statistics, it is noteworthy that a substantial number of institutions have published fewer than three papers in this domain. The size of the nodes in the network graph represents the volume of publications, and the color of the lines indicates the time of the first collaboration between institutions, with darker colors representing more distant years.

**Figure 3.** Co-institution network.

Prominent academic groups have emerged from institutions such as the City University of Hong Kong, Hong Kong Polytechnic University, and Tsinghua University. These universities exhibit varying levels of collaboration, collectively making substantial contributions to CWSRB research.

Concurrently, the figure reveals that certain institutions either conduct independent research or collaborate in the form of small academic groups, such as Hanyang University and the University of Valencia.

Table 3 presents the top 10 institutions ranked by frequency and centrality. The Hong Kong Polytechnic University and City University of Hong Kong lead in publication frequencies, while Tsinghua University exhibits the highest centrality, indicating its active involvement in external collaborations. Noteworthy is the early focus on CWSRB issues by

institutions such as Tsinghua University, the University of Michigan, and Queensland University of Technology before 2013. Post-2015, the inclusion of institutions like Chongqing University, China University of Mining and Technology, and Central South University has further diversified and enriched the research landscape.

Table 3. Top 10 institutions in frequency and centrality.

NO.	Institutions (Frequency)	Institutions (Centrality)
1	Hong Kong Polytechnic University (35)	Tsinghua University (0.23)
2	City University of Hong Kong (35)	Hong Kong Polytech University (0.14)
3	Tsinghua University (26)	City University of Hong Kong (0.1)
4	Huazhong University of Science and Technology (23)	Curtin University (0.08)
5	Chongqing University (19)	Texas A&M University (0.07)
6	Curtin University (16)	Chongqing University (0.05)
7	University of Michigan (13)	Huazhong University of Science and Technology (0.04)
8	Queensland University of Technology (13)	Queensland University of Technology (0.04)
9	China University of Mining and Technology (12)	Southeast University (0.04)
10	Central South University (11)	Michigan State University (0.04)

4.2. Co-Authorship Analysis

To capture collaborative relationships among authors and enhance clarity in graphical representation, we selected the top 40 authors for each time period to construct the network, as depicted in Figure 4.

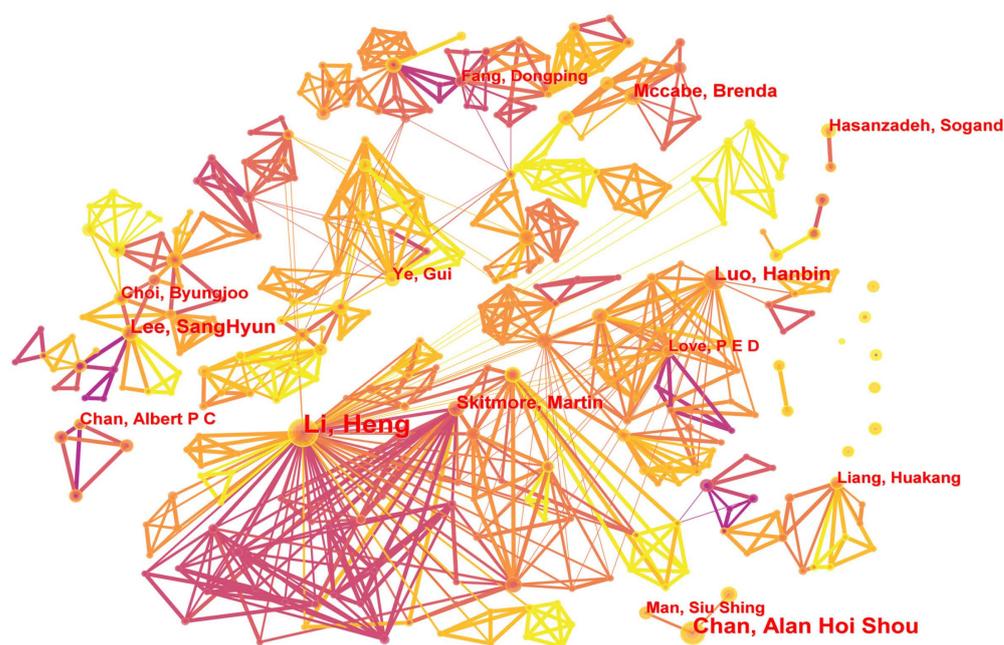


Figure 4. Co-authorship network.

The network comprises 1266 nodes, indicating significant attention to safety issues. The color distribution of nodes suggests a continuous influx of new researchers in this field. Overall, seven sizable academic groups have emerged. Teams led by Lee and Fang have consistently maintained focus, while Li's team currently stands as the largest, engaging in relatively close collaborations with other teams. Ding, Ye, Luo, and McCabe are currently highly active. The teams led by Goh, Y.M.; Chan, A.P.C.; and Chan, A.H.S., either maintain weak connections with the sizable research teams or conduct independent research. The

distribution of similar-sized research teams is widespread, and the figure does not provide a comprehensive representation.

Top 10 authors in frequency and centrality are shown in Table 4. Li, Heng, with the highest publication frequency, also possesses the highest centrality, serving as a key hub linking different research teams. Notably, Li, Heng's centrality does not exceed 0.1, a characteristic closely related to the structural features of this field, where numerous small-scale research teams are in the field. Investigating these scholars further will enhance our understanding of current research topics and the relationships among them.

Table 4. Top 10 authors in frequency and centrality.

NO.	Authors (Frequency)	Authors (Centrality)
1	Li, Heng (28)	Li, Heng (0.08)
2	Chan, Alan Hoi Shou (17)	Chen, Jiayu (0.06)
3	Luo, Hanbin (12)	Luo, Xiaowei (0.04)
4	Lee, SangHyun (11)	Wu, Chunlin (0.04)
5	Mccabe, Brenda (9)	Zhao, Dong (0.04)
6	Skitmore, Martin (9)	Ahn, Changbum R (0.03)
7	Ye, Gui (8)	Du, Jing (0.03)
8	Hasanzadeh, Sogand (8)	Ye, Gui (0.02)
9	Chan, Albert P C (8)	Luo, Hanbin (0.01)
10	Choi, Byungjoo (8)	Lee, SangHyun (0.01)

5. Co-Word Analysis

Co-keyword analysis is an analysis based on the co-occurrence of keywords within a literature. Keywords play a crucial role in summarizing the essence and focus of a research article [37]. Conducting a keyword analysis aids in understanding the research topics within a field and tracking research hotspots.

5.1. Co-Word Network Analysis

After experimenting with multiple parameter settings to effectively present the co-word network, we set the g-index k to 20. Synonyms were merged, and noise words, such as “worker” and “construction”, were eliminated before constructing the network. The top 20 keywords were extracted based on frequency and centrality, as detailed in Table 5.

Table 5. Top 20 key words in frequency and centrality.

NO.	Keywords (Frequency)	Keywords (Centrality)	NO.	Keywords (Frequency)	Keywords (Centrality)
1	safety climate (174)	USA (0.32)	11	culture (43)	priority journal (0.11)
2	model (112)	fall (0.31)	12	occupational risk (41)	accident prevention (0.1)
3	system (76)	attitude (0.26)	13	perception (40)	identification (0.1)
4	accident (76)	behavior based safety (0.16)	14	fall (36)	human resource management (0.1)
5	health (72)	safety engineering (0.16)	15	attitude (36)	social identity (0.1)
6	injury (50)	occupational accident (0.15)	16	deep learning (35)	musculoskeletal system (0.1)
7	construction site (49)	hazard identification (0.14)	17	accident prevention (31)	construction site (0.09)
8	impact (48)	action recognition (0.13)	18	human (30)	perception (0.09)
9	risk (48)	PEOPLES R CHINA (0.12)	19	PEOPLES R CHINA (29)	human (0.09)
10	occupational safety (48)	experience (0.12)	20	identification (28)	workplace safety (0.09)

Accidents and occupational health and safety, viewed as consequences of behavior, exhibit high frequencies, indicating the substantial attention given to these issues in the field. Antecedents frequently studied encompass factors like safety climate, culture, attitudes, individual experience, and hazard identification abilities. Research on accident prevention and behavior monitoring and management measures constitutes a primary focus. Falls from heights, a prevalent safety incident on construction sites, have garnered significant

scholarly attention. High frequencies of the keywords “model” and “system” highlight that empirical research through model construction is a primary research approach in this field. The United States and China emerge as two countries receiving notable attention in research within this domain.

5.2. Analysis of Research Evolution

The temporal distribution of keyword nodes is depicted in Figure 5. Examining the distribution of main keywords over time, from 2013 to 2015, the field concentrated on occupational injuries caused by behaviors and influencing factors, including social and organizational factors such as safety climate, culture, and leadership. Subsequent research on the influence of organizational and management factors on related behaviors served as an extension and deepening of these themes. Simultaneously, research commenced on the correlation between personal factors, including attitudes and personal traits, and their corresponding behaviors. Research on individual-level factors and their influences continued to expand, but after 2017, no influential nodes emerged across various levels of factors, indicating the widespread nature of influencing factors.

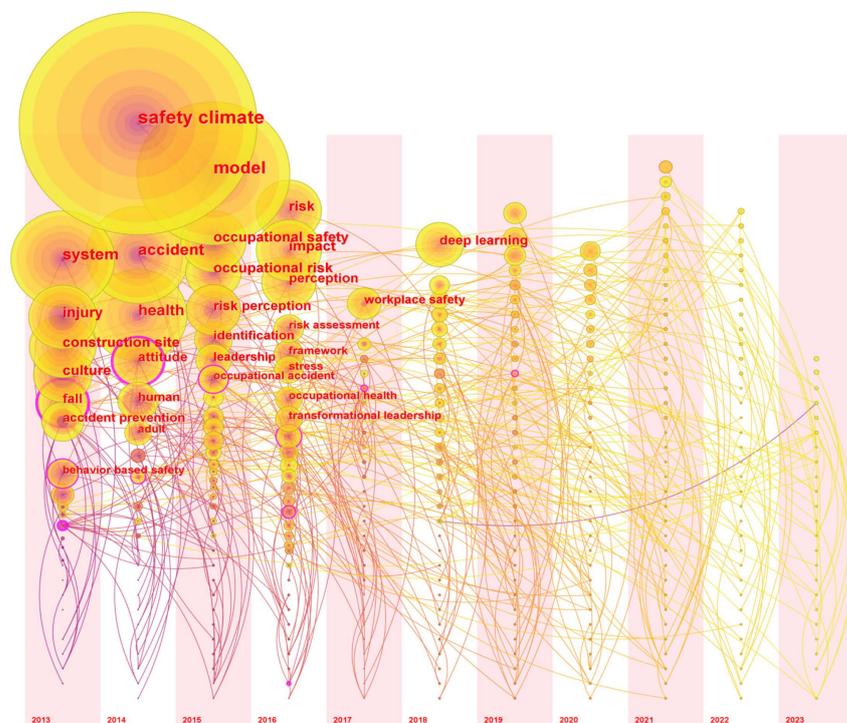


Figure 5. Keyword time zone.

During this period, the supervision and control of unsafe behaviors also became a research focus. Behavior-based safety constituted one of the primary theoretical foundations, and the introduction of information technology represented an exploration of practical applications in terms of methods and techniques, including image recognition and on-site trajectory tracking. Subsequently, with the advancement of information technology, newer technologies were employed for the identification, monitoring, and prediction of unsafe behaviors, such as deep learning in 2018, neural networks and computer vision in 2019, and virtual simulation in 2020, all of which represented research efforts at the technological intervention level.

6. Document Co-Citation Analysis

When two documents are cited together by a third document, they form a co-citation relationship [38]. Analyzing document co-citation relationships can reflect the core concepts, knowledge base, and research progress in a field.

6.1. Analysis of Highly Cited Literature

With a slice parameter of 1 and a g-index k of 20, a co-citation network was constructed. Despite the large number of nodes, only 71 documents have been cited more than 10 times, indicating a relatively concentrated research foundation in this field. Table 6 presents the top ten highly cited documents in the field.

Notably, these highly cited documents primarily originate from the core authors and their teams identified in the co-authorship network analysis. In terms of content, the documents mainly focus on exploring the influencing factors of unsafe behaviors [19,39], the impact of safety climate [40,41], image recognition of unsafe behaviors [42,43], and explanations of unsafe behavior formation from psychological and cognitive perspectives [44–46].

Table 6. Highly cited documents.

NO.	Title	Count	Year	Author
1	Risk-taking behaviors of Hong Kong construction workers—A thematic study [39]	44	2017	Man, S.S., et al.
2	Predicting safety behavior in the construction industry: Development and test of an integrative model [40]	43	2016	Guo, B.H.W., et al.
3	Effects of Safety Climate and Safety Behavior on Safety Outcomes between Supervisors and Construction Workers [41]	36	2020	He, C.Q., et al.
4	Falls from heights: A computer vision-based approach for safety harness detection [43]	33	2018	Fang, W.L., et al.
5	A deep hybrid learning model to detect unsafe behavior: Integrating convolution neural networks and long short-term memory [42]	32	2018	Ding, L.Y., et al.
6	How safety-related stress affects workers' safety behavior: The moderating role of psychological capital [44]	29	2018	Wang, D., et al.
7	The psychological contract: A missing link between safety climate and safety behaviour on construction sites [45]	29	2019	Newaz, M.T., et al.
8	Proactive behavior-based safety management for construction safety improvement [47]	26	2015	Li, H., et al.
9	Impact of the Supervisor on Worker Safety Behavior in Construction Projects [19]	25	2015	Fang, D.P., et al.
10	A Cognitive Model of Construction Workers' Unsafe Behaviors [46]	25	2016	Fang, D.P., et al.

Regarding the time frame, while the publication data were collected from 2013 to 2023, the earliest publication year of the highly cited documents is 2015, indicating that the main research topics in this field emerged after 2013. Simultaneously, five of the highly cited documents were published in 2018 or later, reflecting the current research trends and directions in the field. For instance, a highly cited document published in 2020 provides an in-depth discussion of the influence of safety climate on safety behavior [41], highlighting the enduring relevance of the safety climate topic.

6.2. Document Co-Citation Cluster Analysis

CiteSpace cluster analysis explores research trends and directions in a field by dividing a large amount of data into different units based on their degree of association [48]. A cluster analysis was performed on the document co-citation network, utilizing the log-likelihood ratio (LLR) to generate cluster labels. After scrutinizing the co-cited and citing documents in the main clusters, clusters 7# and 11# were excluded due to their weak association with the research topic or lack of distinct themes. The remaining 11 major clusters are illustrated in Figure 6.

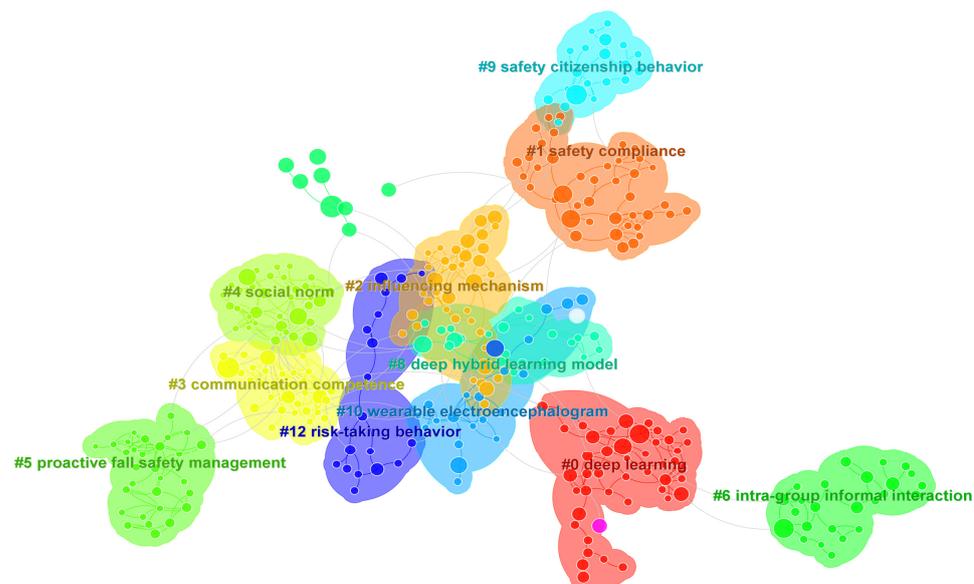


Figure 6. Document co-citation cluster.

The modularity (Q) indicates the significance of the clustering structure, with a consensus that a Q-value greater than 0.3 suggests a significant clustering structure. The silhouette (S) serves as an indicator of the rationality of the clustering, with a common threshold of $S > 0.5$ to consider a cluster as reasonable. The Q value of the clusters is 0.8511, and the S value is 0.94, indicating a significant and reasonable cluster structure. Table 7 provides detailed information about the 11 clusters. The “Size” column represents the number of co-cited documents contained in each cluster, offering insights into the research intensity in that area. For instance, the “deep learning” cluster comprises 44 documents, making it the most actively researched topic in the field. The “Mean (year)” column indicates the average year of appearance for the co-cited documents in the cluster, providing insights into the evolution of the underlying knowledge base for the respective research topic.

Table 7. Summary of co-citation clusters.

Cluster ID	Cluster Label (Log-Likelihood Ratio)	Size	Silhouette	Mean (Year)
0	deep learning	44	0.926	2018
1	safety compliance	41	0.933	2019
2	influencing mechanism	38	0.888	2016
3	communication competence	34	0.937	2014
4	social norm	34	0.919	2013
5	proactive fall safety management	30	0.981	2012
6	intra-group informal interaction	25	1	2019
8	deep hybrid learning model	22	0.966	2015
9	safety citizenship behavior	20	0.979	2018
10	wearable electroencephalogram	20	0.943	2016
12	risk-taking behavior	18	0.901	2018

Clusters 0#, 8#, and 10# all reflect the application of new technologies in the field. Cluster 0# encompasses several highly cited documents [42,49], and the publication years of both the cited and citing documents suggest that deep learning has been a prominent research focus in recent years. Within cluster 8#, co-cited documents exhibit an earlier average year, providing a knowledge base encompassing behavior cognition [46], BBS practices [47,50], and image recognition [22] for the application of image recognition technology in unsafe behavior monitoring, accident prediction, and safety training.

Clusters 1#, 3#, 4#, and 6# predominantly delve into the impact of various factors on behavior. From a temporal perspective, clusters 3# and 4# have an earlier overall publication

history. These published documents serve as the foundation for subsequent research. The more recently established cluster 1# delves into a broader spectrum of influencing factors, such as temporal leadership [20] and individual exposure experience [51], and focuses on safe behaviors within specific groups [52]. It also refines the categorization of safe behaviors, distinguishing between surface compliance and deep compliance [53]. Cluster 6# places emphasis on interactive factors and investigates the dynamic identification and prediction of unsafe behaviors.

The influence mechanism explored in cluster 2# represents a pivotal research pathway in the field, where the pathways, magnitudes, and interactive effects of multiple factors are examined based on identified influencing factors. Meanwhile, cluster 5# indicates that early research on falls from heights primarily centered around real-time positioning technology [54] and human biomechanics [55]. Clusters 9# and 12# reflect an interest in specific types of CWSRB, such as safety citizenship behavior and risk-taking behavior.

7. Thematic Results

The knowledge map conducted a macro and structured analysis of the research field. Based on this, the paper conducts a micro-level inductive analysis of specific research frameworks and outcomes within the field through content analysis. It delineates five key research topics within the field, elucidating areas that require further exploration.

7.1. Concepts and Characteristics of CWSRB

Safety-related behavior is defined as workplace behavior that affects individuals or workplaces from personal threats or injuries [56], encompassing both safe and unsafe behaviors. Scholars within the field have approached this multi-dimensional concept from various perspectives.

Drawing on established practices in general occupational safety research [57], He et al. categorized safe behavior into compliance and participation dimensions [41]. Meanwhile, Yan et al. introduced the concepts of surface compliance and deep compliance, further refining safety compliance behavior [53]. Liu et al.'s research delved into the extra-role attribute of safety participation behavior [57], introducing the concept of safety citizenship behavior [58]. In recent years, relevant studies have primarily examined safe behavior in terms of obedience and proactivity.

Unsafe behavior manifests in diverse ways. Man et al. used risk-taking behavior to describe unsafe actions, encompassing both active and passive unsafe behaviors [39]. Feng et al. [59] introduced risk compensation behavior, emphasizing the proactive nature of construction workers engaging in unsafe behavior. Yuan et al. [60] categorized unsafe behavior into three types: psychological cognitive scarcity, institutional environment scarcity, and attitude–climate scarcity. Other interpretations of the constituent dimensions of unsafe behavior, such as violation behavior [61] and error behavior [62], exist. From existing research, a consensus on the concept and composition of unsafe behavior has yet to emerge.

Simultaneously, characteristics of behavior, such as individual differences [63] and transmissibility [18], have been recognized or verified by researchers in the field, providing valuable insights into understanding the formation of safety-related behavior.

7.2. Influencing Factors and Consequences of CWSRB

The exploration of influencing factors in CWSRB represents a crucial facet of research within this field. Methodologically, data are predominantly acquired through interviews or questionnaires, allowing for the extraction of pertinent influencing factors. For example, Wong et al. [64] conducted 60 face-to-face interviews with construction workers in Hong Kong and identified key factors influencing the use of protective equipment by workers from the qualitative data collected. Low et al. [65] identified personal and organizational factors of risky behaviors through survey questionnaires. The convergence of psychological science, neuroscience, and safety science has ushered in innovative research approaches,

such as utilizing wearable devices to discern the relationship between relevant factors and CWSRB [66].

The identified influencing factors span multiple levels, encompassing macro-level elements such as regulations [60] and culture [15]; meso-level factors like organizational climate [45], group interactions [18], and leadership behavior [19]; and micro-level factors such as individual experiences [51] and physiological and psychological characteristics [67]. As our comprehension of safe behavior deepens, additional influencing factors continue to emerge, as exemplified by Fang et al.'s identification of influencing factors for unsafe behavior rooted in the psychological decision-making process [68]. The influencing factors of CWSRB are diverse and intricate, often arising from the interplay of multiple factors [13,17]. In general, the initial research in this field placed a greater emphasis on identifying distal factors at the macro- and meso-levels, such as economic policies and organizational structures. However, recent studies have shifted their focus towards micro-level factors, delving into the personal attributes and behaviors of individuals within the construction industry. Concurrently, it is crucial to ascertain the contexts in which these factors operate, as unsafe behavior, being the outcome of individual and situational interactions, necessitate consideration within specific contexts despite the multitude of influencing factors.

The consequences of CWSRB are typically associated with accidents and physical injuries, with research methodologies primarily grounded in accident investigation and analysis [11]. Near misses constitute another category of consequence resulting from unsafe behavior. Near misses act as precursors to accidents, where a few missing factors prevent the near miss from escalating into an accident [69]. Research on near misses provide additional insights into the link between relevant behaviors and accidents/injuries. Horizontally, accidents and physical injuries represent outcomes of behavior, but longitudinally, these behavioral outcomes may exert influence on the subsequent behavior of construction workers, a dimension that necessitates careful consideration.

7.3. Formation Mechanisms of CWSRB

The primary focus in analyzing the formation mechanisms involves validating the relevance of influencing factors to CWSRB, as well as exploring the pathways of influence. Throughout this analytical process, a diverse range of theoretical perspectives is applied, with commonly utilized foundational theories including information processing theory, cognitive development theory, leader-member exchange theory, and others. Common methodologies encompass case studies, statistical metrics, and system simulations, among which statistical metric research based on structural equation modeling stands out as the most prevalent. For instance, Yang et al. [70], grounded in theories such as regulatory focus, incorporated negative emotions as a mediating variable and regulatory focus as a moderating variable to elucidate how noise affects the safe behaviors of construction workers using structural equation modeling (SEM). Similarly, employing SEM, Man, S.S., et al. [71] investigated the pathways through which individual-level factors such as outcome expectations and risk perception, as well as organizational-level factors like safety promotion policies and safety training, influence the risk-taking behaviors of construction workers. Wu et al. utilized a case study to explore the influence of social capital on safe behavior [72].

Given that behavior is an outcome of multiple interacting factors, there has been notable attention directed toward system dynamics, enabling the exploration of configurations involving various factors influencing CWSRB. Additionally, multi-agent simulations, adept at characterizing scenarios and reflecting interactive relationships between subjects, have garnered significant interest. Jiang et al. [73] utilized system dynamics to construct a simulation model that incorporates elements such as individual characteristics, environmental conditions, management factors, and unsafe behaviors, to explore the formation of workers' unsafe behaviors under multifactorial conditions. On the other hand, Ye et al. [17] focused on the influence of interactions with others on the site on workers' safety cognition and analyzed the formation of construction workers' unsafe behaviors from the perspective of social cognitive processes using multi-agent modeling.

Some researchers analyze behavior formation from the perspective of behavior transmission, as demonstrated by Liang et al., who integrated system dynamics and multi-agent simulation models to simulate individuals' learning of colleagues' safety violation behaviors under various scenarios [74]. A novel approach to analyzing behavior formation involves the use of wearable devices to capture construction workers' behavioral performance under different stimuli. For instance, Lee et al. utilized wearable devices to explore the impact of fatigue on unsafe behavior [75].

The exploration of CWSRB formation mechanisms represents a pivotal aspect of research in this field. Currently, investigations into formation mechanisms are gradually surpassing the limitation of merely exploring relevant relationships by introducing innovative research methods and extending toward establishing causal relationships. Whether examining a relevant or causal relationship, understanding the reason for its occurrence is crucial knowledge for analyzing formation mechanisms. However, existing research has yet to provide a sufficient response to fully unveil the underlying causes.

7.4. Interventions for CWSRB

One approach to intervening in CWSRB involves on-site supervision and correction of unsafe behaviors, also known as behavior-based safety (BBS). Choudhry [50] developed and implemented a behavior-based safety management system on construction sites in Hong Kong, which included elements such as goal setting, feedback, and effective measurement of safe behaviors, to correct unsafe behaviors. This intervention effectively improved onsite unsafe behaviors within a 9-week implementation period. On the other hand, Guo [76] conducted a 30-week BBS intervention in Singapore, which encompassed goal setting, feedback, and safety training, among other content. However, the results indicated that BBS alone did not improve unsafe behaviors; the social and organizational context must also be considered.

Intervention research also focused on factors influencing behaviors. For instance, safety training is regarded as a significant factor affecting unsafe behaviors. Consequently, several scholars are actively engaged in research on safety training to enhance its effectiveness [24,77]. Recognizing the uncontrollable nature of some antecedent factors such as age, gender, and personality, some researchers have delved deeper into the influence process by introducing mediating variables to intervene in the effects. By exploring the pathways through which personality traits influence safety motivation, Hu et al. [78] proposed that the safe behaviors can be affected by satisfying psychological needs. Wang et al. [44] confirmed the moderating role of psychological capital in the impact of safety stress on safe behavior, suggesting that the adverse effects of safety stress on safe behavior can be mitigated through the adjustment of psychological capital. Progress has also been made in the research on the design of management strategies, where Peng et al. [79] introduced an evolutionary game model to compare the differences in behavioral evolution under various management strategies, thereby providing recommendations for the implementation of management strategies in diverse contexts.

Presently, research on interventions has verified the application effects of BBS and safety training programs in specific scenarios [24]. However, the practicality of numerous intervention approaches and strategies still awaits further verification.

7.5. New Technologies in CWSRB Research

Continuous advancements in technology are reshaping CWSRB research, with computer vision, machine learning, human perception data acquisition, and virtual reality standing out as notable representatives.

Within this field, computer vision and machine learning primarily find application in monitoring workers' unsafe behaviors. Han et al. [22] extracted motion data from a three-dimensional human skeleton motion model and utilized computer vision techniques to recognize workers' unsafe actions during ladder climbing, and the results indicate that the proposed framework has the potential to be applied to onsite video monitoring, thereby en-

hancing the efficiency of observing workers' behaviors in the field. Park et al. [80] proposed a vision-based automatic monitoring method for ensuring the proper wearing of helmets by construction site personnel and it was tested on real website videos, demonstrating its potential in facilitating on-site safety monitoring tasks. Teizer et al. [81] employed position tracking and laser scanning devices to identify and analyze spatiotemporal conflicts between walking workers and potential hazards. To address practicality and accuracy concerns in complex site applications, Ding et al. and Fang et al. developed relevant models using deep learning to automatically detect unsafe behaviors during ladder climbing and helmet wearing, respectively [42,49]. As these technologies continue to evolve, improvements in accuracy, efficiency, and timeliness are expected.

Human perception data acquisition techniques help mitigate subjective biases in measuring individuals' physiological and psychological cognitive states. For example, Kim et al. and Wang et al. employed wearable electroencephalogram (EEG) systems to monitor construction workers' attention during construction activities [66,82]. Hasanzadeh et al. [83] utilized eye-tracking technology to examine the impact of knowledge background on construction workers' hazard detection and visual search strategies. These human perception data acquisition techniques offer valuable approaches for comprehending the internal decision-making processes that underlie safe cognitive behavior.

The complexity and high risks inherent in construction sites pose challenges for conducting relevant research and experiments. However, the development and integration of virtual reality (VR) technology have played a pivotal role in overcoming these limitations [84]. For instance, Shi et al. [85] utilized a multi-user VR system to explore the influence of interpersonal learning on workers' safe behaviors, which demonstrates the differences in behavioral choices of construction workers in hazardous situations under different types of signal stimuli. The application of VR technology to safety training offers workers immersive, interactive, and feedback-based training scenarios. Adami et al. [86] demonstrated that VR-based training is more effective in enhancing workers' knowledge, skills, and safe behaviors, while Kim et al. [87] compared the effects of different intervention measures in a safety training scenario constructed using VR. Moreover, VR can be synergistically combined with other technologies for broader applications, as demonstrated by Kim et al. [66], who used VR technology to create a construction scenario for monitoring workers' attention with EEG.

8. Research Gaps and Future Directions

While existing research has demonstrated significant progress in CWSRB, certain critical issues remain inadequately addressed and warrant further exploration.

8.1. Research Gaps

8.1.1. Diversified Definitions of Unsafe Behaviors

According to the cognitive model of unsafe behavior, construction workers' unsafe behaviors originate from biases during specific stages of recognition, with different stages associated with diverse factors [27,46]. Consequently, the concepts of unsafe behavior exhibit inconsistencies, overlaps, or even conflicts. As proposed in existing research, terms such as unsafe behavior [46], risk-taking behavior [39], and risk compensation behavior [59], although all refer to unsafe actions, clearly exhibit differences in scope. Regarding unsafe behavior, there is currently no consensus on its conceptual definition, which poses challenges to the understanding and subsequent research of unsafe behavior.

8.1.2. Explanatory Power of the Formation Mechanism

While existing research has achieved extensive progress in exploring the influence of factors at different levels on CWSRB [20,41,44], contradictory findings and conflicting perspectives have weakened the explanatory power of existing research. For instance, while numerous studies support the positive role of safety knowledge in promoting safe behaviors, the results of Yu et al.'s research challenge this assertion. An increasing body

of research recognizes that safety-related behaviors are often the result of the interplay of multiple factors [13,16], which necessitates a more in-depth analysis of the boundary conditions of influence, the interactive effects of multiple factors, and the cross-level impacts of factors from different strata.

Additionally, the current verification of factor influence relies predominantly on statistical correlations derived from theoretical analysis [60,67], making it challenging to establish sufficient evidence for causal relationships. New technologies can play a crucial role in obtaining objective data and conducting behavioral experiments, serving as powerful tools for establishing causal relationships. Dynamic aspects such as the transformation between safe and unsafe behaviors, the interaction among safety stakeholders, and the longitudinal association between influencing factors and behavioral outcomes require analysis from a dynamic perspective of the behavioral development process. However, there is currently a lack of research addressing the aforementioned issues.

8.1.3. Design of Intervention Plan

Currently, intervention programs rooted in behavior-based safety (BBS) have seen application in engineering practices. However, the inconsistent outcomes highlight the intricate nature of CWSRB [50,76], suggesting that intervention cannot be effectively executed solely through behavior monitoring, feedback mechanisms, and reward–punishment systems. The development of intervention programs must be grounded in an understanding of the cognitive aspects of behavior formation and development, taking into account various contextual factors, including the dynamics within worker groups and the relationship between workers and management personnel. Although integrated approaches to intervention program design have been simulated, effective practical applications remain scarce. The research primarily validated the effectiveness of BBS projects and safety training [76,86], with safety training often assessed in controlled virtual settings and focusing on immediate post-training effects. The consistency of these intervention measures in producing sustained positive effects in real-world environments, their susceptibility to other influencing factors, and the potential for forgetting effects warrant further investigation.

8.1.4. Practicality of New Technologies

The introduction of new technologies has provided technical support for more extensive and diversified research in the field, enriching our understanding of CWSRB and offering avenues to improve the efficiency of behavior monitoring. However, certain barriers persist in the application of these new technologies in engineering practice. These include considerations such as the economic viability of implementing computer vision and machine learning technologies in real construction sites, the accuracy of unsafe behavior recognition in complex background environments, and the faithfulness of VR models in reproducing real scenarios.

8.2. Future Directions

Based on the scientometric analyses, qualitative discussions of mainstream research areas within CWSRB, as well as gap analysis, a few directions in the future study of the domain can be foreseen.

1. Establishing clear classification criteria, delineating the primary characteristics and manifestations of each category, and fostering a cohesive understanding of unsafe behavior will enhance the accumulation of pertinent knowledge. These will offer guidance for designing more targeted and effective intervention measures.
2. In future research, it is essential to attend to the conditional variations in the formation processes of different types of related behaviors. Concurrently, there is a need to expand research methodologies to facilitate the examination of the combined effects of multiple factors and to strengthen the confirmation of causal relationships. Highlighting a dynamic perspective within research is vital for a comprehensive understanding of the emergence and evolution of safe behaviors.

3. There should be an increased focus on discussing the rationale behind intervention plan design and the influencing factors during the implementation process. Concurrently, more attention should be devoted to the methods and standards for assessing the actual effectiveness of intervention programs.
4. The application of new technologies within the field requires, on one hand, enhanced efforts to overcome the technical barriers of transitioning from controlled experimental environments to real construction sites. On the other hand, it necessitates a discussion on the application of technology from aspects such as economic viability, individual privacy, and ethical considerations in technology use.

9. Conclusions

Utilizing bibliometric methods, this study conducted a comprehensive analysis of 563 publications in the field, employing overall descriptive statistics, collaboration network analysis, co-word analysis, and co-citation analysis to delineate the research structure and evolution of the field. This study's outcomes highlight several key insights: (1) journals such as *Safety Science* play a pivotal role in this domain; (2) institutions such as the City University of Hong Kong and Hong Kong Polytechnic University, along with prolific authors like Li, are major contributors to the field; (3) the focus of research has evolved from early organizational factors towards a more diverse range of topics, with deep learning emerging as a significant current research hotspot; (4) this study has identified highly cited studies and 11 primary clusters within the field.

Building upon this analysis, this study delved into an in-depth examination of core authors and the key literature identified in the bibliometric analysis, summarizing research topics within the field and forecasting future research trends. Current research focuses on five areas: safety-related behavior concepts, influencing factors and consequences, formation mechanisms, interventions, and applications of new technologies. Future research directions encompass establishing clear classification criteria for unsafe behaviors, the in-depth analysis of the formation mechanism of CWSRB, the design of intervention plan, and the application of new technologies in practice.

Similar to other reviews in the field, this study has certain limitations. Firstly, in terms of the scope of the literature search, we exclusively considered two major databases and included only English-language journal articles. Secondly, during the literature screening and analysis process, while statistical and bibliometric methods were employed to ensure objectivity, micro-level judgments and analyses of literature content still carry the risk of subjective bias. Nevertheless, this study contributes valuable insights to help researchers gain a comprehensive understanding of the current research status, to explore future research directions, and to enhance stakeholders' recognition and understanding of the safety-related behaviors of construction workers.

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