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Original Research Article

UNVEILING SAFETY PRACTICES AND SAFETY PERFORMANCE MEASUREMENT IN CONSTRUCTION: A BIBLIOMETRIC ANALYSIS

Alaa A.A ELKASEH[1], Rozana ZAKARIA[2], Anees Ahmed VIGHIO[1*], Joanna A. PAWLOWICZ[3], Vikneswaran MUNIKANAN[4], Jam Shahzaib KHAN[5], Shaza Rina SAHAMIR[6], Md Rajuna AHMAD SHAKRI[7]

[1]Faculty of Civil Engineering, Universiti Teknologi Malaysia, Malaysia
[2]Faculty of Artificial Intelligence, Universiti Teknologi Malaysia, Kuala Lumpur, Malaysia
[3]Faculty of Geodesy, Geospatial and Civil Engineering, University of Warmia and Mazury in Olsztyn, Poland
[4]Department of Civil Engineering, Faculty of Civil Engineering, Universiti Pertahanan Nasional Malaysia, Kuala Lumpur, Malaysia
[5]Department of Civil Engineering, Quaid e Awam University of Engineering Science and Technology, Nawabshah, Sindh, Pakistan
[6]Faculty of Architecture, Planning, and Surveying, Universiti Teknologi MARA, Malaysia
[7]Perak State Health Engineering Director, Ministry of Health, Ipoh, Perak, Malaysia

A b s t r a c t

This study critically addresses the ongoing safety challenges within the construction industry which is known as a sector persistently affected by preventable accidents. The research underscores the importance of rigorous safety performance measurement as a key driver for the continuous improvement of Construction Safety Management (CSM). Utilizing a novel science mapping approach, this comprehensive review examines various research in safety performance measurement, delineating the evolution of Construction Safety Performance (CSP) studies. This paper emphasizes bibliometric analysis conducted for a paradigm shift in safety practices and management strategies. The analysis identifies significant contributors, explores research characteristics, and charts the future trajectory of CSP research. The study aims to bridge a critical knowledge gap in CSP literature, providing a holistic perspective anticipated to enhance safety practices across the construction industry. The findings highlight the crucial role of robust safety performance measurement methods in tracking and improving safety outcomes, evaluating policy impacts, and facilitating continuous improvement.

Keywords: safety management practices, construction safety performance, safety performance measurement, bibliometric analysis

[1] Corresponding author: Anees Ahmed Vighio, Faculty of Civil Engineering, Universiti Teknologi Malaysia, Skudai, 81310, Johor Bahru, Malaysia e-mail: anees@graduate.utm.my, telephone: +601139906276

1. INTRODUCTION

The construction industry, one of the largest and fastest-growing sectors globally, dates back to the Palaeolithic Age, between 40,000 and 12,000 B.C. It plays a crucial role in economic growth, contributing significantly to GDP, with an annual income of about $3,000 billion and accounting for 10% of the world's GDP (Brahmachary et al., 2018; Nguyen, 2022). Despite its economic importance, the construction industry is known for high accident rates and hazardous activities (Elkaseh et al., 2023; F. Wang et al., 2022). Construction-related injuries and accidents are notably higher than in other industries, with the U.S. experiencing rates 50% higher than other sectors (Huang & Hinze, 2003; Sanni-Anibire et al., 2020), and similar trends in Japan, Ireland, and the United Kingdom (Williams et al., 2018). Heinrich's research in 1941 revealed that 88% of accidents stem from unsafe actions, 10% from adverse conditions, and only 2% from uncontrollable factors. He emphasized that 98% of these accidents could be prevented with proper safety practices, highlighting the need for improved safety measures in construction (Heinrich, 1941; Marshall et al., 2018). Recent studies on Heinrich's theory have produced mixed results.

Seward et al., (2014) found relevance in Heinrich's safety pyramid in modern construction sites, while Radvanska, (2010) suggested a balanced approach, noting that the theory might not always apply uniformly due to varying safety cultures. Critics argue that focusing on "man failure" could divert attention from systemic issues (Benamara et al., 2020; A. Johnson, 2011). Effective safety management is essential to prevent accidents and ensure workers' health (Benny et al., 2017). Despite efforts to improve safety standards, fatalities remain a significant concern, underscoring the need for innovative safety measures (Awwad et al., 2016; Engler Bridi et al., 2021; M Gunduz et al., 2018; Gurmu, 2019; Zahoor et al., 2016; Zhou et al., 2013). Accurate safety performance measurement is crucial for continuous improvement and effective decision-making in safety management (Basahel et al., 2016; Eisinger et al., 2022; Olutuase, 2014; Yiu et al., 2018).Traditional safety metrics include the Experience Modification Rating (EMR), Lost Time (LT) and Lost Workday (LW) Rates, and the First-Aid Incident Rate (FAIR). Proactive methodologies such as Near Miss (NM) investigations, Jobsite Safety Inspections (JSI), and Behavior-Based Safety (BBS) are also critical (Bektaş, 2023; Bhagwat et al., 2021; Shaikh et al., 2020).

However, existing Construction Safety Performance (CSP) measurement methods have reached their point of diminishing returns, indicating the need for novel and reliable methods (Bhagwat et al., 2021). Ensuring safety in construction is both a moral and legal obligation, requiring a multi-dimensional strategy that includes a deep understanding of root causes, a commitment to safety practices, and effective performance measurement (Ahamad et al., 2022; Elkaseh et al., 2023; Musonda et al., 2008). As the industry evolves, it must integrate advanced technologies, such as wearable devices, IoT sensors, and data analytics, to identify hazards early and foster a culture of safety (Aziz et al., 2021; Chen et al., 2015). The pursuit of safety in construction is an ongoing journey that builds on Heinrich's foundational work. The industry must adopt a comprehensive, technology-driven, and proactive approach to protect workers and ensure sustainability (Ahmad et al., 2023; Bektaş, 2023; B. Wang et al., 2019).

2. KNOWLEDGE GAP, AIMS, AND OBJECTIVES

In the expansive domain of Construction Safety Management (CSM), numerous exhaustive reviews have meticulously scrutinized various facets. These inquiries have delved into subjects such as the integration of cutting-edge technologies (Bhagwat & Delhi, 2021; Fang et al., 2006; Yap et al., 2022), the intricacies pertaining to the safety of construction equipment, notably cranes (Sayler et al., 2019;

Shao et al., 2019), the multifaceted aspects of safety culture and climate (Olugboyega & Windapo, 2019; Shaikh et al., 2020), the formulation of accident causation models (Hosseinian & Torghabeh, 2012; Khanzode et al., 2012), and the broader research landscape encompassing CSM (Bhagwat & Delhi, 2022).

Nonetheless, there remains a noticeable lacuna in the existing literature – a gap demanding attention. This gap resides in the underrepresentation of comprehensive studies dedicated to the meticulous review of the extensive body of knowledge concerning Construction Safety Performance (CSP) literature and its intricate connection to safety practices.

While some studies have explored the factors influencing safety performance in construction projects, there is a noticeable gap when it comes to visually mapping this knowledge using an innovative science mapping approach (Abas et al., 2020; Shaikh et al., 2020). According to (Bhagwat & Delhi, 2021) this novel approach has the potential to create a thorough and structured representation of Construction Safety Performance (CSP) measurement methods and their connections to safety practices. To address this gap, our study aims to conduct an extensive review of CSP measurement methods and safety practices, utilizing the enlightening capabilities of the science mapping approach. Our research is guided by three core objectives, all contributing to a comprehensive understanding of CSP and its multifaceted aspects.

While certain research endeavors have ventured into examining the factors that impact safety performance within construction projects, a noticeable void exists concerning the application of an innovative science mapping approach to visually represent this knowledge (Abas et al., 2020; Shaikh et al., 2020). As articulated by Bhagwat & Delhi, (2021), this innovative approach holds the potential to construct a comprehensive and well-structured depiction of construction safety performance (CSP) measurement techniques and their intricate connections with safety practices. To bridge this gap, our study endeavors to undertake an extensive exploration of CSP measurement methods and safety practices, harnessing the illuminating capabilities of the science mapping approach (Choudhry & Zahoor, 2016; Keffane, 2020). Our research is underpinned by three fundamental objectives, all contributing to a holistic comprehension of CSP and its multifaceted dimensions:

Identifying Influential Contributors: The first objective is an endeavor to identify the most influential contributors in the domain of Construction Safety Performance (CSP) literature. By adopting a multidimensional approach, we seek to shed light on influential countries, organizations, and authors that have made significant contributions to the CSP landscape (Alruqi & Hallowell, 2019; Mohammadi et al., 2018).

Unveiling Research Characteristics: The second objective is to unravel the nuanced characteristics of Construction Safety Performance (CSP) research. This entails a deep dive into focused research levels, the varying types and phases of construction projects that have been under scrutiny, and the research instruments and data sources that have been pivotal in shaping this discourse (Gumilar et al., 2022; Shikdar & Sawaqed, 2003).

Visualizing the Construction Safety Performance (CSP) Landscape: The third objective entails a comprehensive investigation into the measurement methods of construction safety performance (CSP) and essential safety practices. Its goal is to trace the developmental path of research in construction safety performance, decode present research trends, and, significantly, provide insights into future research avenues within the domain of construction safety performance management (Bhagwat & Delhi, 2021).

The overarching ambition of this study is not only to bridge a critical knowledge gap but also to significantly contribute to the broader comprehension of construction safety performance. By constructing a comprehensive visual map of the CSP literature and its intricate web of associated practices, this study aspires to offer invaluable insights to researchers, industry professionals, organizations, and policymakers. It is our steadfast belief that this collective endeavor will markedly enhance safety practices and, in turn, contribute to the overall well-being of all those engaged in the multifaceted world of construction projects.

3. RESEARCH METHODOLOGY: A COMPREHENSIVE SCIENCE MAPPING APPROACH

To fulfil our research objectives, we have embraced an extensive science mapping approach, serving as a robust method for constructing networks that uncover the theoretical, intellectual, and social foundations within the expansive research landscape (Amadeu Dutra Moresi et al., 2021; Ammad et al., 2021a; Bhagwat & Delhi, 2021, 2023). This approach transcends traditional research analysis by making domain knowledge more tangible through scientometric analysis (Akram et al., 2019; Amadeu Dutra Moresi et al., 2021; Umeokafor et al., 2022). Our methodology unfolds through three pivotal steps, each meticulously designed to generate insights and enrich our comprehension of the Construction Safety Performance (CSP) domain. These steps are as follows:
Bibliometric Search: Our study commenced with an exhaustive bibliometric search, systematically aggregating pertinent literature that contributes to the body of knowledge in the Construction Safety Performance (CSP) domain. This initial phase serves as the cornerstone for our subsequent analyses, ensuring that our findings are firmly grounded in an extensive and diverse dataset.

Scientometric Analysis: Subsequent to the bibliometric search, we immersed ourselves in scientometric methods as the core of our analysis. This step entails a quantitative evaluation of the compiled literature, shedding light on the productivity and impact of countries, organizations, and authors within the Construction Safety Performance (CSP) landscape. The scientometric analysis provides a data-driven perspective, enabling us to discern patterns, interconnections, and influential contributors in the field.

Content Analysis: The concluding phase of our science mapping approach encompasses content analysis. During this stage, we delve into the intellectual and theoretical foundations of the Construction Safety Performance (CSP) domain. It offers insights into specific research attributes, such as the focal points of research, the types and phases of construction projects investigated, and the research instruments and data sources employed within the body of literature. Content analysis enriches our comprehension of the Construction Safety Performance (CSP) and provides a comprehensive perspective on the construction safety performance landscape. This robust methodology allows us to explore the CSP domain thoroughly, uncovering hidden connections, trends, and knowledge gaps. It equips us with a deeper understanding of construction safety performance and informs evidence-based decisions for advancing safety practices in the construction industry.

3.1. Bibliometric Search Development

There In 2009, an international group of systematic reviewers, methodologists, clinicians and journal editors disseminated the Preferred Reporting Items for Systematic reviews and Meta Analyses (PRISMA) statement, a guideline designed to help authors prepare a complete report of their systematic review (1-7)Matthew et al., (2021).The establishment of the bibliographic database strictly adhered to the prescribed guidelines outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). These guidelines encompass four distinct phases: identification, screening, eligibility, and inclusion, as delineated in the works of Johnson et al. (2020); Nohman Khan et al. (2020).

The overarching objective of these phases was to systematically aggregate pertinent bibliographic data. Bibliometric analysis is a type of research approach to understand the global research trends in a particular field upon on the outputs of the academic publications such as Scopus or WoS database. Therefore, this type of approach is differentiating between two types of academic research (i.e., review paper and a bibliometric analysis) which primarily discuss the final results of a specific topic. In the pursuit of a comprehensive bibliometric analysis, the Web of Science database was identified as the principal source for this research undertaking. The selection of the Web of Science was grounded in its expansive coverage, which encompasses registrations from over 12,000 global journals and cataloging of more than 160,000 conferences, including international events held across the globe. The database's repository of research articles spans a diverse range of research domains and is recognized for its inclusion of highly influential peer-reviewed research articles, rendering it an ideal choice for this study. This assertion is supported by previous research in the field of 'Construction Safety Performance (CSP), as exemplified by the works of Escamilla-Fajardo et al. (2020), Farooq et al. (2021), Grabowska & Saniuk (2022), Marín-Marín et al. (2021).

The keywords used for our literature search were 'Construction Safety' and 'Construction Safety Performance.' We configured the search criteria to include 'All Years,' articles written in the 'English' language, and those classified as 'Journal Articles.' To illustrate, the search query was structured as TITLE-ABS-KEY: ('Construction Safety Performance') AND DOCUMENT TYPES: (Article) AND LANGUAGE: (English). Our research strategy exclusively focused on peer-reviewed journal articles to ensure strict adherence to rigorous quality standards. In contrast, conference papers were excluded due to their subjectivity in the peer-review process and varying publication standards, as highlighted in previous research by Bhagwat & Delhi (2021); Hardison & Hallowell (2019).

Following our initial keyword search, we unearthed a treasure trove of 1,705 search results for 'construction safety,' accompanied by a more modest 59 results for 'construction safety performance.' Armed with this rich array of resources, we embarked on an intellectual journey, crafting a mosaic of knowledge composed of 1,764 peer-reviewed research journal articles in the English language, thoughtfully sifting through to ensure no duplicates marred our collection. This expansive dataset formed the bedrock of our subsequent screening phase, setting the stage for our scholarly exploration.
During the screening process, a meticulous examination resulted in the identification and subsequent elimination of 62 duplicate research articles. This de-duplication process was conducted with precision using Microsoft Excel and the Mendeley reference management tool. Following this process, a refined dataset comprising 1,702 research articles remained, which were then subjected to evaluation based on a set of four screening criteria established by Bhagwat & Delhi, (2021); Zhou et al., (2013). These criteria encompassed:

- Verification to ensure that the keywords were not repurposed for alternative contexts.
- Thorough assessment to ascertain that the keywords were employed in research with an in-depth investigative approach.
- Scrutiny to confirm that the primary focus of the safety investigations did not predominantly pertain to structural mechanics.
- Validation to ensure that the emphasis on safety performance measurement was not subordinated when juxtaposed with other facets of construction safety. It is important to note that these criteria were flexibly adapted to align with the specific objectives and aims of the present study.

Having completed the meticulous screening process, we identified a staggering 1,429 research articles that did not align with our primary focus on safety performance. These articles were gracefully ushered out of consideration. In their stead, 273 research articles stepped into the spotlight and advanced to the inclusion phase. Each of these 273 selected articles embarked on a journey of exploring safety performance within diverse industrial, organizational, or project settings, employing either reactive or proactive methodologies to illuminate this complex terrain. Our bibliometric quest spanned the rich tapestry of relevant literature from 1981 to 2023, ultimately culminating in the embrace of 273 peer-reviewed research journal articles, elegantly expressed in the English language. These carefully curated articles formed the foundation upon which we embarked on our dual expedition of scientometric and content analyses, unearthing insights and unraveling the intricacies of the field.

3.2 Scientometric Examination

The scientometric analysis is a robust method employed to assess research impact, citations, and collaborative efforts within the scholarly domain. Scientometric is used internationally for monitoring and assessment purposes. Despite its limitations, the field of scientometric tells us much about the health of a country's national innovation system. Monitoring and evaluating the various facets of the scientific enterprise is a necessary and integral part of science policy IM Jacobs et al., (2014). This method possesses the remarkable capability to unveil the dynamic evolution of domain-specific knowledge by creating intricate network maps, reminiscent of the intricate cartography of academic progress as discussed by Donthu et al., (2021). Within our array of scholarly instruments, we have at our disposal a trio of potent tools: VOSviewer, CiteSpace, and Gephi. Among these, VOSviewer is the chosen instrument for our endeavor due to its numerous merits. These include its status as a freely accessible visualization tool, its proficiency in sifting through vast repositories of textual knowledge, and its excellence in generating bibliometric maps that rival the finest work in the field, akin to the contributions of (Chellappa et al., 2021; Liu et al., 2023; Malakoutikhah et al., 2022).

3.3 Comprehensive Examination of Scholarly Content: An In-Depth Analysis

Content analysis serves as a meticulous research technique, akin to a seasoned explorer, aimed at extracting reliable and replicable insights from written and significant materials. It delves deep into the contextual landscape within which these materials hold significance (Bhagwat & Delhi, 2021; DeJulio et al., 2020; Kim et al., 1985; White & Marsh, 2006). This method employs two distinct brushes, resembling those of a versatile artist: quantitative content analysis, which quantifies findings through numerical representation, revealing frequencies, rankings, or ratings, and qualitative content analysis, which plunges into the intricate nuances of text to unveil hidden meanings and significance (Devi Prasad, 2019; Schreier et al., 2020).

Within the scope of our study, both methodological brushes harmoniously contributed to the exploration of multifaceted dimensions. They collaboratively painted a canvas that illuminated the research's characteristics, diverse approaches to measuring Construction Safety Performance (CSP), the tapestry of safety practices, the ever-evolving CSP research landscape, the prevailing trends, and the promising research directions on the horizon. To orchestrate this artistic endeavor, we harnessed the power of NVIVO software, specifically version NVIVO 12, as a digital curator for the systematic coding and examination of the literary treasures we unearthed.

4. SCIENTOMETRIC ANALYSIS AND GLOBAL CONTRIBUTIONS IN CONSTRUCTION SAFETY PERFORMANCE RESEARCH

4.1. Exploring Scientometric Insights

Our research expedition embarked with the meticulous assembly of an extensive research article database, meticulously curated through a rigorous bibliometric exploration. This valuable dataset was then transformed into a structured comma-separated values (XLS) file format, akin to the organized cataloguing of historical manuscripts, and seamlessly integrated into the VOSviewer tool, an indispensable instrument for conducting a comprehensive scientometric analysis. The scientometric journey unfurled methodically, akin to an unfolding scroll of knowledge, comprising two pivotal phases: document and citation analysis, complemented by an exhaustive co-authorship exploration. Furthermore, our scholarly inquiry delved into a nuanced research phase analysis, serving as a temporal lens to gain profound insights into the evolving research trends spanning the years from 1981 to 2020. This analysis was thoughtfully partitioned into three distinct research phases, each bearing the weight of its historical context: Phases 1, 2, and 3, encapsulating the periods from 1981 to 1999, 1999 to 2009, and 2010 to 2023, respectively. The fruits of these rigorous scientometric investigations have uncovered a trove of invaluable insights and discernible trends, poised to be expounded upon and dissected in the forthcoming sections of our scholarly odyssey.

4.2. Analysis of Citations and Documents

This section presents a comprehensive analysis of yearly publication trends, document characteristics, and citation patterns within the Construction Safety Performance (CSP) domain. Each scientific domain is unique, necessitating separate analyses. Our document and citation analysis investigated annual publication trends and quantified research articles from various countries, organizations, and authors. This analysis aimed to highlight shifts in research output over time and across different scholarly entities. The citation analysis tracked the frequency of article references and citations to assess scholarly influence and impact. It examined citation patterns of countries, organizations, and individual authors, revealing their contributions and influence within the academic landscape.

4.3. Yearly publications

The examination of yearly publications provides a comprehensive overview of the trajectory of Construction Safety Performance (CSP) research. Since its inception in the late 20th century, CSP research has consistently garnered attention from safety researchers, underscoring its enduring relevance and importance, as illustrated in Table 1. The data reveals a clear trend of sustained growth in research publications, with a notable increase beginning in the early 2000s. This continuous rise in publication numbers reflects a growing awareness and recognition of CSP within the industry.

Table 1. Yearly Publications

Publication Years	Record Count	Publication Years	Record Count	Publication Years	Record Count	Publication Years	Record Count
2022	303	2014	34	2004	8	1995	2
2023	271	2013	32	2006	8	2000	2
2021	253	2010	21	2007	8	1981	1
2020	193	2012	18	1997	5	1982	1
2019	173	2009	17	1999	5	1983	1
2018	98	2011	14	1993	4	1990	1
2017	76	2005	13	1996	4	1991	1
2016	70	2008	13	1998	3	2002	1
2015	69	2003	8	2001	3		

The peak in 2022, marked by 303 publications (17.474% of the total 1,734 records), represents a significant culmination of efforts in the field, highlighting an intensified focus on safety and productivity in contemporary construction practices. The diverse range of publication years, spanning from the mid-1990s to 2023, emphasizes the long-term impact and relevance of CSP research. Additionally, the inclusion of earlier records from 1981, 1982, and 1983, along with scattered publications throughout the 1990s, underscores the historical evolution of CSP research.

In summary, the data delineates the progressive journey of CSP research, showcasing its enduring appeal, increasing recognition, and the industry's sustained commitment to enhancing safety and productivity in construction practices over the past few decades.

4.4. Worldwide Publications

This analysis investigates the CSP research domain through country-based, organization-based, and author-based perspectives. The top five countries by publication percentage Table 2a are China (48.5%, 845 articles), the USA (23.7%, 414 articles), Australia (9.9%, 174 articles), South Korea (7.7%, 135 articles), and England (5.5%, 97 articles).

Table 2. results of a research investigation focused on CSP (country, organization, and author).

COUNTRY-BASED INVESTIGATION						**ORGANIZATION-BASED INVESTIGATION**						**AUTHOR-BASED INVESTIGATION**					
a			**b**			**c**			**d**			**e**			**f**		
Top Five Countries by Publication %			**Top Five Countries by Citation Count**			**Top Five Organizations by Publication %**			**Top Five Organizations by Citation Count**			**Top Five Authors by Publication %**			**Top Five Authors by Citation Count**		
Country	**NA**	**Pp**	**Country**	**Citation.**	**Tls**	**Org.**	**NA**	**Pp**	**Org.**	**Citation**	**Tls**	**Authors**	**NA**	**Pp**	**Authors**	**Citation**	**Tls**
China	845	48.5%	USA	772	6	Hong Kong Polytechnic Uni	92	5.22%	Uni Of Florida	280	1	Li H	33	1.7%	Behm, M	269	0
USA	414	23.7%	China	295	9	Tsinghua Uni	64	3.63%	East Carolina Uni	269	0	Albert A	30	1.7%	Hinze, Jimmie	251	2
Australia	174	9.9%	Australia	184	4	Huazhong Uni of Science Technology	53	3.01%	Uni Fluor Corporation	251	1	Goh YM	30	1.7%	Thurman, Samuel	251	2
South Korea	135	7.7%	England	94	3	National Uni of Singapore	50	2.83%	Uni Of Canberra	141	3	Chan APC	29	1.6%	Wehle, Andrew	251	2
England	97	5.5%	Canada	92	2	State Uni System of Florida	47	2.66%	Uni Of New South Wales	141	3	Liao PC	24	1.3%	Anderson, S	164	2

In terms of citation counts Table 2b, the leading countries are the USA (772 citations), China (295 citations), Australia (184 citations), England (94 citations), and Canada (92 citations). Examining organizations, the top five by publication percentage Table 2a are Hong Kong Polytechnic University (5.22%, 92 articles), Tsinghua University (3.63%, 64 articles), Huazhong University of Science and Technology (3.01%, 53 articles), National University of Singapore (2.83%, 50 articles), and State University System of Florida (2.66%, 47 articles). The top five organizations by citation count Table 2b are the University of Florida (280 citations), East Carolina University (269 citations), Fluor Corporation (251 citations), the University of Canberra (141 citations), and the University of New South Wales (141 citations). Author-based investigation highlights the top five authors by publication percentage Table 5a as Li H (1.7%, 33 articles), Albert A (1.7%, 30 articles), Goh YM (1.7%, 30 articles), Chan APC (1.6%, 29 articles), and Liao PC (1.3%, 24 articles). The top five authors by citation count Table 5b are Behm, M (269 citations), Hinze, Jimmie (251 citations), Thurman, Samuel (251 citations), Wehle, Andrew (251 citations), and Anderson, S (164 citations).

4.5. Organization Publications and Contributions in Construction Safety Performance Research

In this scholarly investigation, 99 organizations engaged in Construction Safety Performance (CSP) research, focusing on the top contributors as shown in Table 2c, 2d. Notably, 'The Hong Kong Polytechnic University' and 'Tsinghua University' emerged as leading contributors with 92 and 64 research articles respectively, representing 5.22% and 3.63% of the total publications. 'Huazhong University of Science and Technology' and 'National University of Singapore' followed with 53 and 50 articles respectively. In terms of citations, 'The Hong Kong Polytechnic University' achieved the highest scores, followed by 'University of Florida' and 'East Carolina University.' Early CSP research (Phase 1) was predominantly led by these institutions, with later phases involving other distinguished organizations such as 'China University of Mining and Technology,' 'NC State University,' and 'University of Colorado Boulder,' reflecting a growing global interest and engagement in CSP research.

4.6. Co-authorship analysis

This study delved into the expansive landscape of Construction Safety Performance (CSP) research, identifying a collaborative network involving 70 countries, 1,419 organizations, and 4,142 researchers. The co-authorship analysis meticulously traced the research linkages between these entities, with network maps highlighting highly interconnected countries, organizations, and individual researchers to visualize the dynamic networks within the CSP domain. Table 2 results offer insights into these collaborations, particularly focusing on the top contributors. As depicted in Table 2(e) and Table 2(f), the most prolific authors in terms of publication percentage include Li H. (1.7%), Albert A. (1.7%), Goh YM. (1.7%), Chan APC (1.6%), and Liao PC (1.3%). In terms of citations, the leading authors are Behm M. (269 citations), Hinze Jimmie (251 citations), Thurman Samuel (251 citations), Wehle Andrew (251 citations), and Anderson S. (164 citations). These visualizations and findings serve as critical tools for understanding the intricate fabric of collaborations, illustrating the global and organizational affiliations shaping the CSP research landscape, and highlighting the significant contributions and interdependencies driving advancements in this field.

4.7. Worldwide co-authorship network

The global co-authorship network, illustrated in Figure 1, shows collaborations across countries. Nodes represent countries, organizations, or authors, with sizes reflecting publication volumes. Link thickness indicates Total Link Strength (TLS), the number of co-authored publications. Figure 1 highlights key collaborations: the USA (TLS = 6), China (TLS = 9), and Australia (TLS = 4).

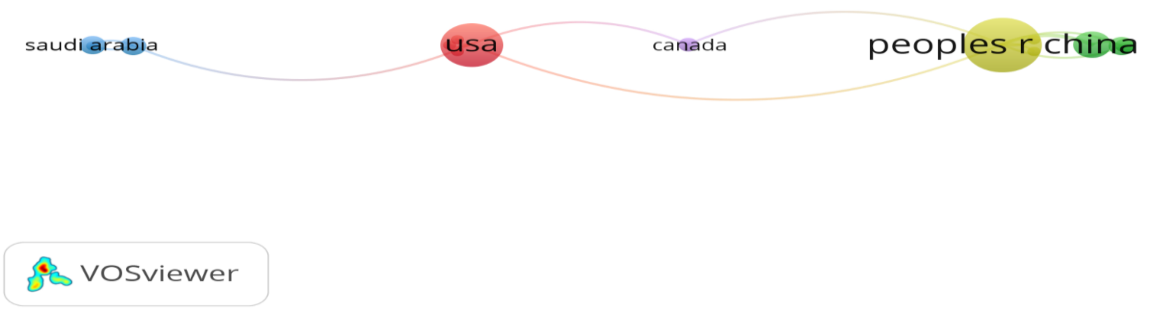

Fig. 1. The global co-authorship network through VOSviewer network visualisation

Poland and Saudi Arabia are increasingly collaborating with major players like the USA, China, and Hong Kong. Citation counts are led by the USA (772), followed by China (295) and Australia (184), indicating their research impact. Emerging countries like Poland and Saudi Arabia show promising growth in research collaborations.

4.8. Organization Co-authorship Network

The investigation reveals collaborative efforts among diverse organizations in research studies, forming an organization co-authorship network Figures 2. Each node represents an organization, with node size indicating the number of attributed publications and connections denoting collaborative efforts, measured by Total Link Strength (TLS). The University of Florida stands out in the network, notable for its significant citations (280) and active collaboration. The University of Canberra and the University of New South Wales also display robust co-authorship networks (TLS = 3), highlighting their engagement in research initiatives. East Carolina University and Fluor Corporation follow closely in impact, with the University of Florida and other organizations making substantial contributions to the CSP research domain. Ben-Gurion University of the Negev has notable collaborations in this field. The collaborative landscape underscores the University of Florida's strong co-authorship network (TLS = 1), with active participation from institutions such as Arizona State University, Faithful Gould, and the University of Colorado, indicating a vibrant research environment.

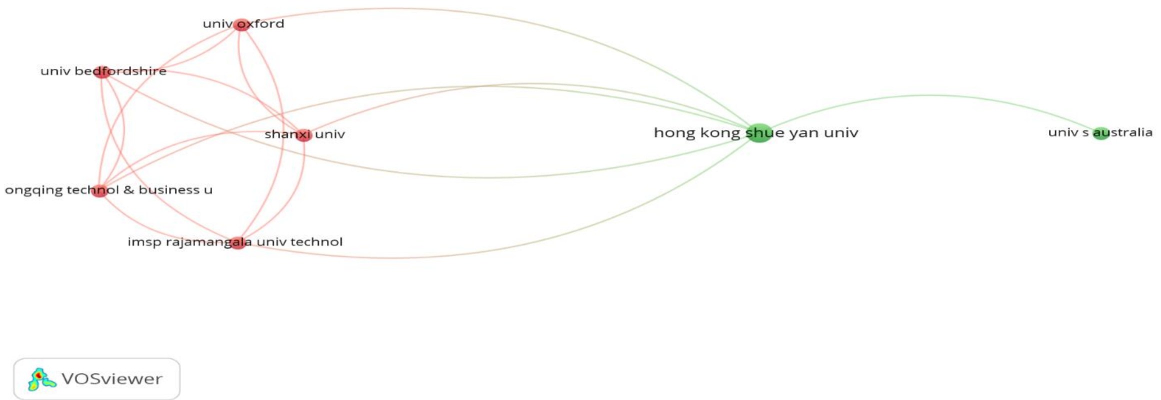

Fig. 2. Co-authorship network based on organizations illustrated through VOSviewer network visualization

4.9. Author Co-authorship network

This study explores the co-authorship network in 147 research articles, with 145 resulting from collaborative efforts. Figures 3 illustrate the network of research collaborations, highlighting highly connected nodes representing authors. The Total Link Strength (TLS) quantifies the strength of collaboration, indicating the number of co-authored articles. Notable authors identified from Table 1(f) include 'Behm, M.' with the highest citation count (269) but no significant collaborative links (TLS = 0).

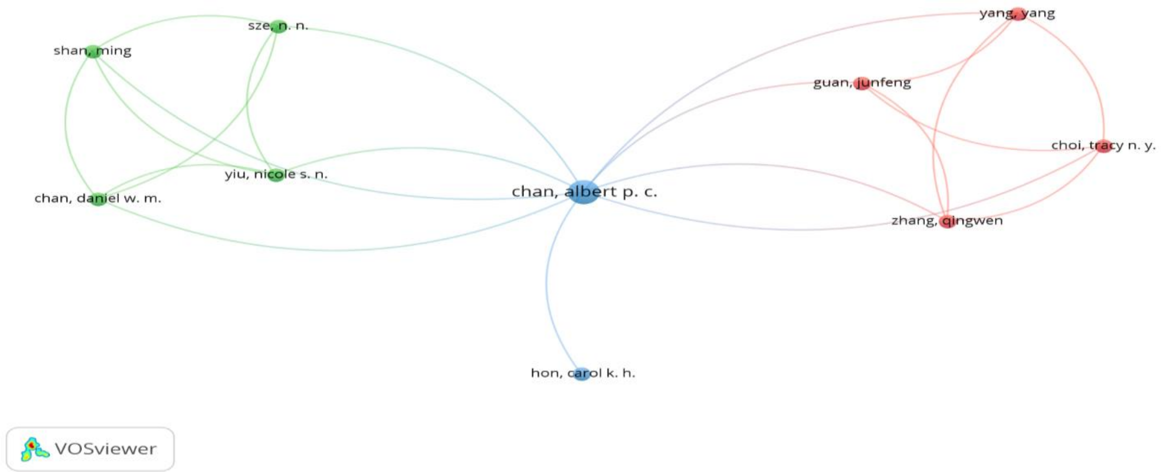

Fig. 3. Co-authorship network based on authors showcased through VOSviewer network visualization

In contrast, 'Hinze, Jimmie,' 'Thurman, Samuel,' and 'Wehle, Andrew' exhibit considerable co-authorship networks, each with a TLS of 2. 'Zhou, Zhipeng' stands out with a notable citation count (113) and a robust co-authorship network (TLS = 9), indicating extensive collaboration. The research phases analysis shows 'Hinze, Jimmie' initiating CSP research in the first phase with other researchers. Subsequent phases saw active participation from authors like 'Sunindijo, Riza Yosia' and 'Zou, Patrick X. W.,' indicating a sequential progression of collaborative research in this field.

5. FINDINGS AND DISCUSSIONS

5.1. Quantitative Content Analysis

This study delves into the multifaceted dimensions of Construction Safety Performance (CSP) research through quantitative content analysis. The comprehensive analysis examines various aspects, including research levels, project classifications, project phases, research instruments, and data sources. By meticulously examining these elements, we uncover numerous factors influencing CSP research, providing a deeper understanding of its intricate landscape.

5.2. Research Levels in Construction Safety Performance (CSP) Research

Our analysis identifies three primary research levels within CSP research: industry, organization, and project. Industry-level research predominates, comprising 66% of the total articles reviewed, followed by project-level research at 27%, and organization-level research at 6%. This trend underscores the industry's concerted effort to develop comprehensive safety solutions applicable across diverse project types. The prevalence of industry-level research highlights the broader impact and importance of safety standards that transcend individual projects (Neamat, 2019; Trtílek & Hanák, 2021).

5.3. Project Typology and Construction Phases

The study conducts a thorough analysis of eight distinct project types, revealing a significant focus on building projects, which comprise 27% of the total publications. Other project types, such as airport projects, receive considerably less attention, with only 1% of the publications addressing this category. This disparity suggests a heightened focus on safety within the global building construction industry, possibly due to historical accident rates and robust safety awareness initiatives. Additionally, the research emphasizes the execution phase of projects as a critical area for safety performance studies, highlighting its essential role in ensuring effective safety protocols and practices.

5.4. Research Instruments

Our investigation identifies six primary research instruments utilized in CSP studies. The questionnaire survey emerges as the most prevalent tool, used in 45% of the total publications, followed by the interview technique and case study methods, employed in 25% and 20% of the studies, respectively. The reliance on traditional methods such as surveys and interviews over advanced visualization models like Building Information Modelling (BIM) suggests a preference for manual data collection techniques. This reliance highlights the potential for future research to explore and integrate more innovative technological advancements in assessing CSP (He et al., 2019; Muzafar, 2019; Saka & Chan, 2020).

5.5. Data Sources

The study catalogs sixteen distinct data sources used in CSP research. Management personnel emerge as the most frequently referenced data source, cited in 20% of the publications. Other significant data sources include safety personnel (16%), workers (15%), and supervisory personnel (13%). The integration of diverse perspectives from these key stakeholders indicates a robust safety culture prevalent within CSP research. This comprehensive approach ensures a thorough understanding of safety dynamics from multiple vantage points, contributing to more effective and inclusive safety protocols (Bavafa et al., 2018; Y. Li et al., 2018; Zainol et al., 2020).

6. QUALITATIVE CONTENT ANALYSIS

Given the lack of extensive prior knowledge on CSP, an inductive qualitative content analysis was conducted. This analysis encompasses a wide range of facets within CSP research, including methods for measuring CSP, prevalent safety practices, the evolution of CSP research, and emerging trends in the field.

6.1. Methods for Measuring Construction Safety Performance (CSP)

CSP is traditionally assessed through both reactive (lagging indicators) and proactive (leading indicators) approaches. Reactive methods include metrics such as lost time rates and recordable incident rates, which provide insights based on past incidents and accidents. In contrast, proactive methods emphasize early detection and intervention, utilizing tools like near-miss incidents and safety perception surveys. These proactive approaches aim to identify potential hazards before they result in accidents, thereby enhancing overall safety performance and prevention strategies (Bhagwat & Delhi, 2021; Salhi & Messaoudi, 2021; Trtílek & Hanák, 2021).

6.2. Construction Safety Practices

Through qualitative content analysis, the study identifies 133 distinct safety practices categorized into 11 primary safety dimensions. These dimensions range from safety rules and regulations to hazard identification and risk analysis. The implementation of these practices across various projects underscores their importance in enhancing CSP. For instance, practices related to personal protective equipment (PPE) and safety planning play crucial roles in mitigating risks and ensuring safe working conditions. The comprehensive categorization and analysis of these safety practices provide valuable insights for improving safety protocols within the construction industry (Aloiseghe et al., 2021).

6.3. Evolution of Construction Safety Performance (CSP) Research

The evolution of Construction Safety Performance (CSP) research has significantly reshaped safety paradigms within the construction industry. Initially grounded in perception-based and behavior-based paradigms, CSP research incorporated engineering principles to ensure structural integrity and embed safety protocols. Over time, it integrated insights from diverse fields such as Construction Building Technology, Operations Research Management Science, and Psychology, leading to refined safety assessments (Awwad et al., 2016; Ibrahimkhil & Hadidi, 2021). Recent advancements have emphasized proactive safety management, leveraging AI, machine learning, and visualization technologies like BIM, VR, AR, and MR to enhance safety monitoring and management (Ammad et al., 2021; He et al., 2019). The inclusion of Social Sciences has further strengthened safety culture, emphasizing human interactions and communication (Elsebaei et al., 2022; Tong et al., 2018). This evolution has also incorporated machinery and materials science insights, ensuring robust safety protocols in the deployment of heavy equipment (Y. Li et al., 2018; Rodrigues & Matos, 2019). Qualitative and quantitative analyses reveal a shift from reactive to proactive safety management, highlighting the importance of leading indicators and automation technologies (W. T. Chen et al., 2019; Othman et al., 2020). This transformation underscores a commitment to safer, more resilient construction environments, prioritizing human well-being and structural integrity (Ajmal et al., 2021; Al-Shehri et al., 2013).

6.4. Advancements in Current Research Trends for Construction Safety Performance

The construction industry continually seeks improved safety practices, driven by recent academic advancements utilizing predictive methodologies and emerging technologies. Predictive methods, like neural networks and digital twins, anticipate hazards by correlating design parameters with safety performance (Halim et al., 2016; Zhu & Wang, 2022). Research highlights factors impacting safety, such as incident learning, information flow, safety culture, and external events (Andrijanto et al., 2022; Casady & Baxter, 2020; Davey et al., 2021; Zhao et al., 2016). Technologies like AI, VR, wearable devices, and drones enhance proactive monitoring and real-time risk assessment (Akinsemoyin et al., 2023; Awolusi et al., 2018; Choi et al., 2017; Gheisari & Esmaeili, 2019; R Y M Li, 2017; Rita Yi Man Li, 2017; Lu & Davis, 2016; Rokooei et al., 2023). Additionally, behavioral studies on cognitive processes and team dynamics emphasize the importance of human factors in safety. Sophisticated evaluation models and safety metrics provide nuanced insights for developing effective intervention strategies (Guldenmund, 2000; Küçükarslan et al., 2023). These trends promise a future where safety is paramount, ensuring worker well-being and elevating industry standards through technological and behavioral innovations.

7. CONTRIBUTIONS TO THE THEORETICAL AND PRACTICAL DIMENSIONS OF CSP KNOWLEDGE

This study significantly enhances our understanding of Construction Safety Performance (CSP) by providing both theoretical and practical insights. It explores the philosophies of key contributors, examining reactive and proactive approaches across various research levels, project scopes, phases, and data sources. The study underscores the importance of proactive safety measurement strategies and presents a foundational CSP management framework, which serves as a blueprint for future advancements in safety protocols. Practically, the research promotes integrating proactive strategies with robust data capture methods, encouraging the use of Job Safety Information (JSI) checklists, Behavior-Based Safety (BBS) investigations, and systematic employee surveys to foster a safety-oriented culture. The study also identifies critical gaps in aligning proactive safety measures with International Standards Organization (ISO) benchmarks, highlighting the need for collaboration among industry stakeholders, regulatory bodies, and the ISO to refine standards. Addressing these gaps will enhance safety measures across construction sites, strengthen the CSP knowledge base, and advance safety management practices in the construction industry.

8. CONCLUSIONS

Ensuring safety in the construction industry is a continuous and adaptive process. While Heinrich's foundational work provided initial insights into accident causation, the modern construction sector necessitates a more comprehensive and technology-driven approach. This study extensively examined Construction Safety Performance (CSP) literature through an innovative science mapping approach, resulting in a detailed visual map of safety practices and measurement methodologies. Our findings highlight the importance of robust safety performance measurement methods. These methods are essential for tracking and improving safety outcomes, evaluating policy impacts, and facilitating continuous improvement. Advanced technologies and proactive methodologies, such as wearable devices, IoT sensors, and data analytics, are vital in pre-emptively identifying potential hazards. Additionally, strategies like Behavior-Based Safety (BBS), Jobsite Safety Inspections (JSI), and Safety Perception Surveys (SPS) play a crucial role in fostering a culture of safety. The commitment to safety within the construction industry is both a moral and economic imperative. Ensuring safety is fundamental to the industry's growth, workforce well-being, and its contribution to society. As the industry faces new challenges and opportunities, it must remain adaptable and innovative, employing best practices and advanced technologies. This study underscores that achieving safety in construction is a multifaceted and dynamic goal that requires concerted efforts from all stakeholders. By continuously advancing our understanding, integrating new technologies, and adopting a proactive mindset, the industry can achieve higher safety standards. This commitment to safety is essential not only for the welfare of workers but also for the sustainability and success of the construction sector. Through collective endeavors, the construction industry can significantly enhance safety practices, contributing to a safer, more resilient, and sustainable future for construction worldwide.

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