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EXPLORING METHODS AND TRENDS IN EVACUATION SAFETY RISK ASSESSMENT IN HIGH-RISE BUILDINGS: A SYSTEMATIC LITERATURE REVIEW AND BIBLIOMETRIC MAPPING

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ABSTRACT

Evacuation safety risk assessment (ESRA) in high-rise buildings is a critical area of study due to the complex structural, functional, and occupancy characteristics that influence evacuation performance during emergencies. Over the past decade, researchers have introduced a range of simulation techniques, computational models, and analytical frameworks to examine evacuation efficiency, human behavior, and system performance. However, limited work has consolidated these approaches in a systematic manner. In addition, existing studies remain fragmented across simulation, behavioral, and technological domains, with limited integration of emerging artificial intelligence approaches, creating a gap in achieving a holistic understanding of ESRA. This study addresses this gap by providing a critical and integrated synthesis, contributing new knowledge through the identification of structural research limitations and uncovering relationships between key themes using a combined systematic literature review (SLR) and bibliometric mapping approach. This study conducted a SLR on ESRA in high-rise buildings. Using Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, 25 articles published between 2020 and 2025 were identified from Scopus, Web of Science, and ScienceDirect. Bibliometric mapping using VOSviewer revealed four dominant clusters, including fire safety, high-rise building risk factors, evacuation strategies, and emerging deep learning applications. The findings show that simulation-based and engineering-focused studies remain central, while artificial intelligence approaches are growing but remain underutilized. The systematic review also identified four major themes: building type, technology and smart systems, evacuation strategies, and methods used. Overall, this review provides a structured overview of current research trends, identifies gaps in existing approaches, and offers insights to guide future studies and practical risk management efforts in high-rise buildings.

Keywords: *Evacuation Safety Risk Assessment, High-Rise Buildings, PRISMA, Risk Management, Systematic Literature Review*

1. INTRODUCTION

Evacuation safety risk assessment (ESRA) in high-rise buildings has become an increasingly

important area of research due to the growing density of urban populations and the complexity of modern building designs [1]. High-rise structures pose unique challenges during emergencies, as evacuation is often hindered by factors such as vertical circulation, occupant density, limited exit routes, and reliance on technological systems [2]. According to [3], ensuring safe and efficient evacuation, therefore, requires robust building designs complemented by comprehensive evaluation methods that integrate human behavior, building characteristics, and potential hazards. Such assessments are essential for advancing safety strategies and mitigating risks in high-rise environments.

Various approaches have been developed to assess evacuation safety, including computational modeling, simulation tools, and field-based studies [4], [5]. These methods enable researchers and practitioners to evaluate potential risks, predict evacuation performance, and design interventions to enhance safety. Furthermore, recent studies highlight the integration of smart technologies, sensor systems, and advanced algorithms to improve real-time monitoring and decision-making during emergencies [6], [7]. Despite the increasing body of literature, research on ESRA remains fragmented, with studies often focusing on specific aspects such as fire evacuation, human behavior, or technological systems, rather than providing a holistic overview [8].

Despite the growing volume of ESRA research, several critical limitations remain evident. Existing studies are often confined to isolated analytical dimensions, such as fire dynamics [9], evacuation simulation [10], or behavioral modeling [11], without sufficiently integrating these components into a unified framework. This fragmentation restricts the ability to capture the complex and interdependent nature of real-world evacuation scenarios. Moreover, many studies rely heavily on simulation-based environments, which, although computationally efficient, may not fully reflect the uncertainty, variability, and adaptive human responses observed during actual emergencies [12]. Consequently, there is a need for a more critically synthesized understanding of ESRA that not only consolidates existing findings but also evaluates its limitations and practical applicability.

Similar to challenges in other research domains, existing literature reviews on evacuation safety in high-rise buildings often lack systematic approaches. Traditional reviews may be selective, introducing transparency and bias issues [13]. Consequently, a systematic literature review (SLR) is necessary to consolidate current knowledge, identify emerging trends, and highlight gaps in ESRA research. By applying the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, this study aims to provide a structured and transparent analysis of existing research on evacuation safety in high-rise buildings.

The primary objective of this SLR is to explore the methods and trends in ESRA. Specifically, this study aims to i) identify the types of high-rise buildings, ii) examine the methods and technologies used to conduct evacuation assessments, iii) analyze the evacuation strategies of ESRA research, and iv) highlight the methods involved in evacuation studies. The findings of this review will offer valuable insights for both researchers and practitioners, providing guidance for enhancing evacuation safety in high-rise environments. Alongside the systematic review, this study employs bibliometric mapping to visualize keyword co-occurrences, identify dominant research clusters, and capture the intellectual structure of ESRA studies over the past five years. The remaining sections of this paper are structured as follows: Section 2 presents the Methods, Section 3 summarizes the Results of the literature analysis, Section 4 discusses the Findings in detail, and Section 5 is the Conclusion that identifies gaps and recommendations for future study.

2. METHODS

The primary objective of a SLR is to methodically identify, examine, and synthesize existing research relevant to a specific topic or phenomenon. This process is carried out transparently and consistently, using reproducible procedures at each stage to ensure rigor and reliability. Systematic reviews are sometimes described as meta-narrative or mixed reviews, reflecting their capacity to integrate diverse strands of literature. As noted by [14], a SLR represents a comprehensive and structured approach to identifying, evaluating, and interpreting all available studies pertinent to a defined research question or area of inquiry. However, distinguishing between established knowledge and research gaps remains a demanding task, highlighting the importance of predefined and explicit methodological procedures. In this study, the PRISMA framework was employed to guide the SLR on ESRA in high-rise buildings.

PRISMA is widely recognized for its effectiveness in ensuring transparency and methodological rigor in systematic reviews. It has been applied successfully across multiple domains, including the social sciences [15], educational technology [16], engineering [17], and medical [18]. Figure 1 shows that the PRISMA framework encompasses four fundamental stages: identification, screening, eligibility, and data abstraction and analysis.

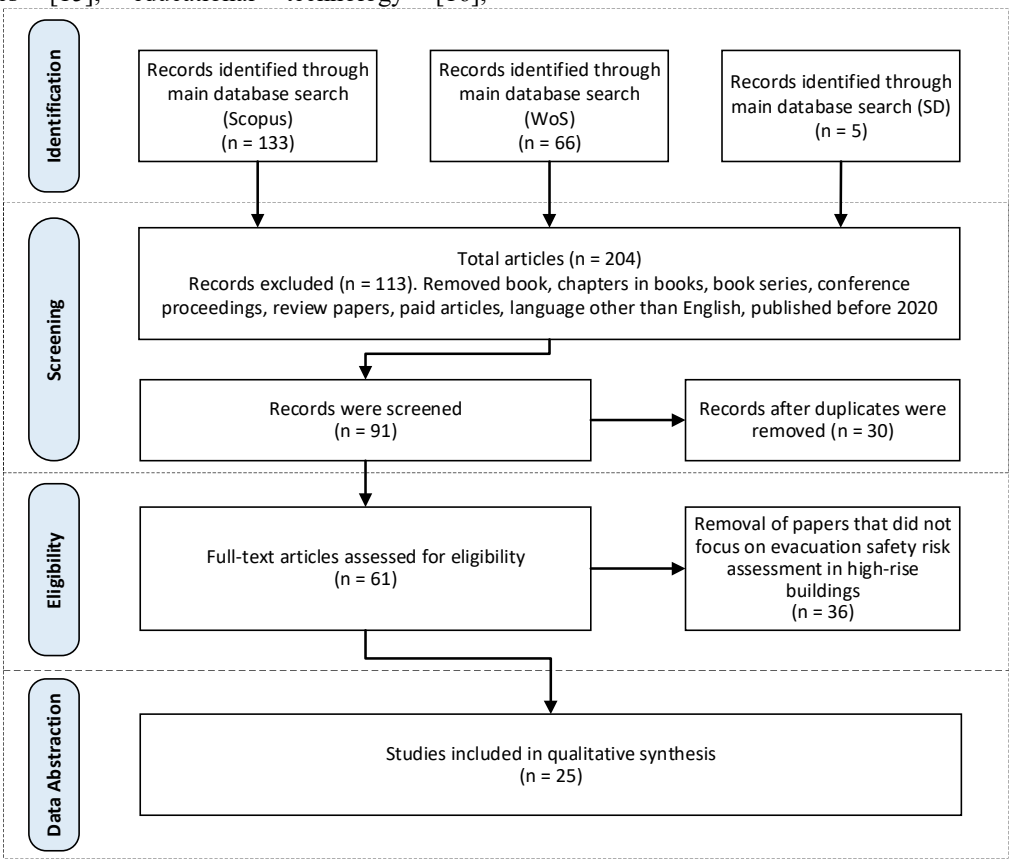

Figure 1: PRISMA Flow Diagram (Online Databases' Identification of Studies)

2.1 Identification

Figure 1 illustrates the steps involved in implementing the PRISMA approach. The literature search process initially identified 204 articles based on predefined selection criteria, comprising 133 from Scopus, 66 from Web of Science (WoS), and five from ScienceDirect (SD). This stage of identification was carried out using the sorting functions provided by the respective databases, with uniform criteria applied consistently across all platforms. In cases where database tools were insufficient, articles were manually screened and removed. Given the vast number of publications available, it is often impractical for researchers to evaluate all studies comprehensively. Hence, [19] emphasized the importance of establishing a specific timeframe to manage the review process effectively.

The selection criteria focused on substantial review articles and empirical research employing relevant keywords, as outlined in Table 1. A comprehensive search strategy was applied using Boolean operators such as "OR" to refine the scope of the results. The primary databases consulted were Scopus, WoS, and SD, while Google Scholar (GS) was used as a supplementary source when access restrictions were encountered. Overall, the search process yielded more than 204 articles, of which 25 were identified as relevant and included in the final review.

Table 1: Search String Used in Selected Database.

Database	Search String
Scopus	TITLE-ABS-KEY((“evacuat*” OR “egress*” OR “escap*” OR “exit*”) AND (“safe* risk*” OR “risk* analysis*” OR “risk* evaluat*” OR “risk* manag*” OR “hazard* analysis*” OR “safe* manage*” OR “risk* mitigat*” OR “risk* model*” OR “safe* perform*” OR “vulnerabl* assess*” OR “disaster* risk*” OR “accident* risk*” OR “hazard* risk*” OR “emergenc* risk*” OR “risk* profil*” OR “vulnerabl* analys*”) AND (“tall* build*” OR “skyscrape*” OR “multi-storey*” OR “multistory*” OR “high-rise*” OR “vertical* build*” OR “tower* block*” OR “tower*” OR “high-densit*” OR “high* densit*”))
WoS	TS = ((“evacuat*” OR “egress*” OR “escap*” OR “exit*”) AND (“safe* risk*” OR “risk* analysis*” OR “risk* evaluat*” OR “risk* manag*” OR “hazard* analysis*” OR “safe* manage*” OR “risk* mitigat*” OR “risk* model*” OR “safe* perform*” OR “vulnerabl* assess*” OR “disaster* risk*” OR “accident* risk*” OR “hazard* risk*” OR “emergenc* risk*” OR “risk* profil*” OR “vulnerabl* analys*”) AND (“tall* build*” OR “skyscrape*” OR “multi-storey*” OR “multistory*” OR “high-rise*” OR “vertical* build*” OR “tower* block*” OR “tower*” OR “high-densit*” OR “high* densit*”))
SD	(“evacuation” OR “egress”) AND (“safety risk” OR “risk analysis” OR “hazard risk” OR “emergency risk”) AND (“tall building” OR “skyscrape” OR “high-rise”)

2.2 Screening

Next, the process involved was the screening stage. An examination of the search results from the designated databases revealed that publications related to ESRA in high-rise buildings have shown a notable increase beginning in 2020 and continuing through August 2025, acknowledging that the current year is still ongoing. Accordingly, the time interval from 2020 until 2025 was established as an inclusion criterion. To ensure the quality of the review, only peer-reviewed journal articles containing empirical data were considered. During the screening phase, 113 papers were excluded for not meeting the predetermined inclusion criteria, leaving 91 publications deemed eligible for further evaluation.

This review focused exclusively on English-language studies addressing ESRA in high-rise buildings. Table 2 presents the inclusion and exclusion criteria applied. The research articles that were discovered focused on ESRA in high-rise buildings. Non-research papers such as review papers, conference proceedings, theses, chapters, and books were excluded from the SLR.

Table 2: The Criteria for Inclusion and Exclusion.

Criteria	Inclusion	Exclusion
Publication Time	2020-2025	2019 and earlier
Document Type	Journal (research articles)	Other than journal
Language	English	Non-English
Focus of Research	ESRA in high-rise buildings	Not related to evacuation safety risk assessment in high-rise buildings
Country	Worldwide	(N/A)

2.3 Eligibility

The eligibility phase constituted the third stage of the review process, during which the retrieved articles were manually examined to ensure alignment with the predefined inclusion criteria. Titles and abstracts were screened as an initial filter, while full texts were assessed in cases where relevance remained uncertain. In this phase, 30 articles were excluded for several reasons, including duplication across databases, non-English language publications, limited relevance to ESRA in high-rise buildings, and instances where the articles were review papers rather than empirical studies. Following this process, 61 articles were confirmed as eligible for inclusion in the SLR.

2.4 Data Abstraction and Analysis

The final phase, data abstraction, encompassed the systematic extraction and in-depth analysis of relevant information from the eligible studies. In this stage, 25 articles were retained for comprehensive review, while 36 were excluded on the grounds that they did not specifically address ESRA in high-rise buildings. The inclusion of articles was guided by their alignment with the research questions and objectives, ensuring that only studies of direct relevance were analyzed. Data were carefully obtained through the detailed examination of titles, abstracts, and full texts, followed by a structured evaluation to extract pertinent content. The subsequent analysis applied thematic procedures to uncover prevailing trends, patterns, and gaps in the literature, with particular attention to

similarities, differences, and overarching concerns identified across the selected articles.

To ensure rigor in the thematic process, the study employed the six-step thematic analysis framework outlined by [20], which has been recognized as an appropriate and reliable method for qualitative synthesis. The procedure commenced with an intensive familiarization process through repeated readings of the 25 articles to achieve a deep understanding of their content. The second step involved systematically identifying recurring commonalities and key divergences among the studies, which served as the foundation for further categorization. The third stage emphasized the construction and refinement of themes derived from these observed patterns, ensuring conceptual clarity and coherence. The fourth step required iterative verification to ensure that the emerging themes maintained consistency with the central context and objectives of the reviewed articles. This methodological process ultimately enabled the identification of four major themes that encapsulated the essential findings of the review. The fifth and sixth steps involved consolidating these themes into an organized structure and generating a comprehensive synthesis of the results, which collectively contributed to the development of the final report of the SLR.

Lastly, bibliometric mapping was conducted to complement the systematic review and to visualize the intellectual structure of evacuation safety risk assessment research. VOSviewer version 1.6.20, developed by [21], was used to generate keyword co-occurrence maps based on the author keywords extracted from the selected articles. The software applies a co-occurrence counting technique and constructs a network representation where nodes indicate keywords and links represent their co-occurrence relationships within the data. This process enables the identification of research clusters, thematic concentrations, and emerging topics in the literature. All keywords were standardized prior to analysis to ensure consistency, and only terms that met the minimum occurrence threshold were included in the mapping. The resulting visualization provides an overview of dominant themes and interconnections among concepts relevant to evacuation safety in high-rise buildings.

3. RESULTS

Table 3 shows the overall review of the collected 25 articles from China, India, Malaysia, Nigeria, South Korea, Chile, Colombia, United Kingdom, United States of America, and Vietnam. Figure 2 illustrates the frequency of research papers collected from 2020 to 2025. The number of publications fluctuated during this period. Specifically, there was a decline from 2020 to 2021 (from three to one article), followed by an increase from 2021 to 2022 (from one to three articles). The trend continued upward between 2022 and 2023 (from three to five articles) and rose sharply from 2023 to 2024 (from five to eight articles). However, in 2025, the number of publications slightly decreased to five articles from eight articles. This reflects the fact that the review only considered studies published up to September 2025, as the year has not yet concluded.

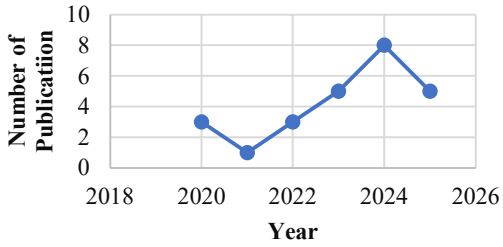

Figure 2: Number of Publications Related to Evacuation Safety Risk Assessment in High-Rise Buildings

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Table 3: Matrix Table on SLR Research Study from 2020 to 2025.

Author	Countries	Building Type							Technology and Smart System								Evacuation Strategies							Method Used										
		RB	OB	CC	MF	SA	GHB	EB	IoT	DP	FDS	PS	PF	BA	DS	SM	PE	VH	BE	IE	TE	PME	MLR	LR	MC	YL	ABM	AHP	FCE	FEM	LM	CNN	RNN	DELM
[22]	N	X																X	X					X										
[23]	CL					X							X								X		X		X		X							
[24]	SK						X			X								X																
[25]	CN	X							X									X								X								
[26]	CN		X													X		X												X				
[27]	V	X												X		X		X													X			
[28]	UK	X												X				X		X		X	X											
[29]	M	X																X																
[30]	CB				X	X							X			X		X												X				
[31]	N						X							X				X	X			X		X										
[32]	CN						X						X					X	X		X	X					X	X	X					
[33]	M		X											X				X	X			X												
[34]	I	X													X			X		X		X						X	X					
[35]	USA	X												X				X	X	X		X												
[36]	CN	X								X					X			X																
[37]	I	X									X	X	X					X				X					X							
[38]	CN					X				X				X			X				X													
[39]	CN		X											X			X	X			X													
[40]	CN				X						X	X	X					X																
[41]	CN			X							X	X	X				X	X																
[42]	SK	X								X								X																
[43]	CN		X							X								X	X							X						X	X	
[44]	CN							X		X			X		X						X	X					X							X
[45]	I						X			X					X		X								X		X						X	
[46]	CN					X							X	X							X						X					X		

Countries	Theme 1: Building Type	Theme 2: Technology and Smart System	Theme 3: Evacuation Strategies	Theme 4: Method Used
N = Nigeria CL = Chile SK = South Korea CN = China V = Vietnam UK = United Kingdom M = Malaysia CB = Colombia I = India USA = United	RB = Residential Building OB = Office Building CC = Commercial Complex MF = Medical Facilities SA = Stadium/Arena GHB = General High-Rise Building EB = Educational Building	IoT = Internet of Things DP = Building Information Modeling (BIM)/ Geographic Information System (GIS) Disaster Platform FDS = Fire Dynamics Simulator PS = PyroSim PF = Pathfinder BA = Behavioral Analysis DS = Decision-making System SM = Seismic Modeling	PE = Phased Evacuation VH = Vertical and Horizontal Evacuation (Stairs, Elevators, Shafts) BE = Behavior-driven Evacuation IE = Inclusivity-focused Evacuation TE = Total / Simultaneous Evacuation PME = Policy/Management-led Evacuation (Training, Drills, Manager Roles)	MLR = Multiple Linear Regression LR = Logistic Regression MC = Monte Carlo YL = YOLOv5 ABM = Agent-Based Modeling AHP = Analytic Hierarchy Process FC = Fuzzy Comprehensive Evaluation FEM = Finite Element Method LM = Levenberg–Marquardt CNN = Convolutional Neural Network RNN = Recurrent Neural Network

The adaptation of the thematic analysis yielded the establishment of four main themes encompassing a total of 33 subthemes. These included building type with seven subthemes, technology and smart systems with eight subthemes, evacuation strategies with six subthemes, and methods used with 12 subthemes. The distribution of these themes and subthemes was quantified and presented statistically, thereby illustrating the frequency of occurrence of the 33 subthemes across the analyzed articles.

Figure 3 depicts the distribution of articles across the main themes and their associated subthemes, as identified through the thematic analysis. The highest frequency was observed within the building type theme, where residential buildings were the most extensively examined, appearing in 10 studies. Pathfinder has the highest number of studies for technology and smart system, appearing in eight studies, followed by vertical and horizontal evacuation (stairs, elevators, shafts) for evacuation strategies with 20 studies, and agent-based modeling for methods used in six studies.

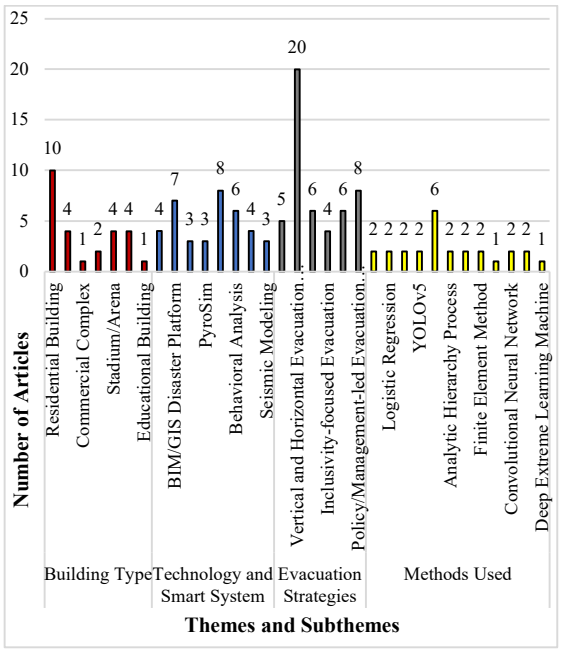

Figure 3: Themes and Subthemes Based on the Articles

Figure 4 illustrates the summary percentages of the four main themes among the 33 subthemes. The building type theme comprised 21% (7 of 33 subthemes), while technology and smart systems accounted for 24% (8 of 33 subthemes). The largest share was observed in evacuation strategies, which represented 18% (6 of 33 subthemes). Finally, the methods used theme constituted 37% (12 of 33 subthemes). Consequently, it can be concluded that research on ESRA in high-rise buildings has been distributed relatively evenly across the four themes, with technology and smart systems emerging as the most frequently represented areas. Pathfinder is the most used technology and smart system, with eight articles in total.

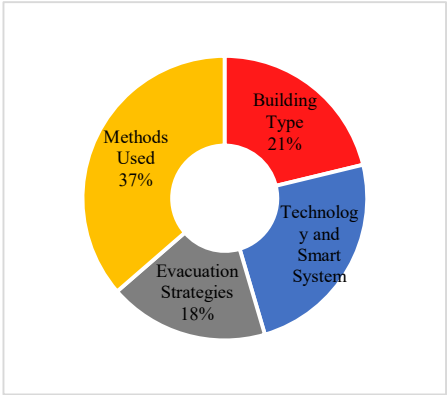

Figure 4: Summary Percentage of Theme Distribution

4. DISCUSSION

The purpose of conducting a systematic review is to critically examine the trends of ESRA in high-rise buildings. In addition, the bibliometric mapping serves to quantify the scientific landscape of this topic by identifying publication patterns, influential contributors, and emerging research themes. The evaluation of evacuation safety and risk assessment is crucial, as it contributes to improving the resilience of occupants and the overall safety performance of high-rise structures. Based on the analysis, 25 selected papers were categorized into four major themes, namely, 1) building type, 2) technology and smart system, 3) evacuation strategies, and 4) methods used.

4.1 Bibliometric Mapping

The bibliometric mapping conducted through keyword co-occurrence mapping reveals four major thematic clusters that define the intellectual structure of evacuation and fire-safety research in high-rise contexts. Figure 5 presents the co-occurrences of authors' keywords, showing the most frequently appearing terms and their total link strengths across the dataset. The keywords evacuation, fire safety, and high-rise buildings appear with the highest occurrences and strongest connections, indicating their central role in shaping current research on evacuation safety risk assessment. Deep learning and emergency

evacuation also demonstrate notable link strengths, reflecting the emergence of computational and data-driven approaches within the field.

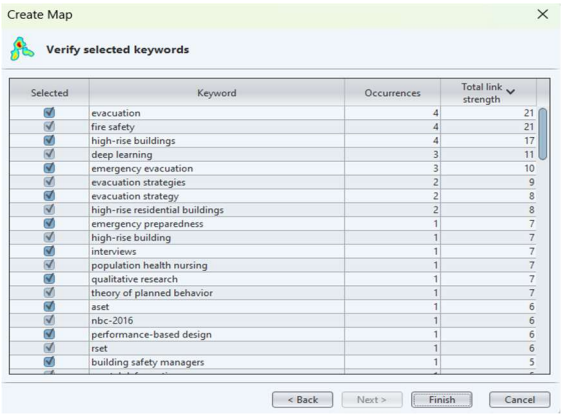

Figure 5: Co-Occurrences of Authors' Keywords

The first and most prominent cluster centres on fire safety, which emerges as the conceptual core of the field. Keywords such as fire simulation, fire behavior, and emergency preparedness demonstrate that the literature is heavily anchored in engineering-based analyses concerned with fire dynamics and occupant responses during emergency scenarios. The density and centrality of this cluster indicate that fire-safety considerations continue to guide both methodological and practical directions across the research domain. The second cluster focuses on high-rise buildings, specifically highlighting keywords related to indicators, fire risk mitigation, and the development of assessment methods. The strong linkage between this cluster and the fire-safety cluster suggests that high-rise studies remain primarily situated in the context of fire hazards, rather than encompassing a broader multi-hazard perspective. This indicates both a deep reliance on established fire-engineering frameworks and a potential research gap in the application of evacuation studies to non-fire emergencies within tall-building environments.

Next, the third cluster represents evacuation and public safety, encompassing terms such as evacuation, architectural programming, public safety, and qualitative research. This cluster reflects an interdisciplinary orientation that integrates behavioral science, architectural design, and emergency planning. The presence of qualitative-related keywords signals a growing, although still limited, interest in human-centered approaches that examine decision-making, situational behavior, and preparedness. However, the relatively smaller size and fewer connections of this cluster indicate that behavioral and social perspectives remain less dominant compared to simulation-driven engineering studies. The fourth and emerging cluster relates to deep learning and advanced computational modelling, represented by keywords such as deep learning, extreme learning machine, YOLO-based recursive neural network, simulation, and large public building. This cluster is positioned at the periphery of the network yet displays clear bridging links to evacuation research. Its structure suggests the rise of data-driven and AI-enhanced methodologies that support tasks such as occupant detection, flow prediction, and automated emergency decision-support. However, the limited direct connection between this AI cluster and high-rise building keywords indicates that deep learning remains an underutilized tool in high-rise building evacuation research, highlighting an opportunity for integration in future studies.

Taken together, the network visualization demonstrates that the domain is still dominated by traditional engineering and simulation approaches, with emerging but fragmented adoption of artificial intelligence and behavioral-based methods. Figure 6 illustrates the network visualization of co-occurrences of authors' keywords based on the 25 studies with four main clusters. The thematic distribution highlights a field that is evolving toward computational intelligence but has not yet fully bridged methodological silos between fire engineering, evacuation behavior, high-rise design, and deep learning. While the presence of deep learning indicates a shift toward data-driven approaches, its peripheral position suggests that such methods are not yet fully embedded within mainstream ESRA research. This fragmentation highlights a critical structural limitation in the field, where methodological silos persist and interdisciplinary integration remains underdeveloped. Consequently, future research must move beyond isolated advancements and focus on developing unified frameworks that bridge engineering precision, behavioral realism, and intelligent data-driven modeling.

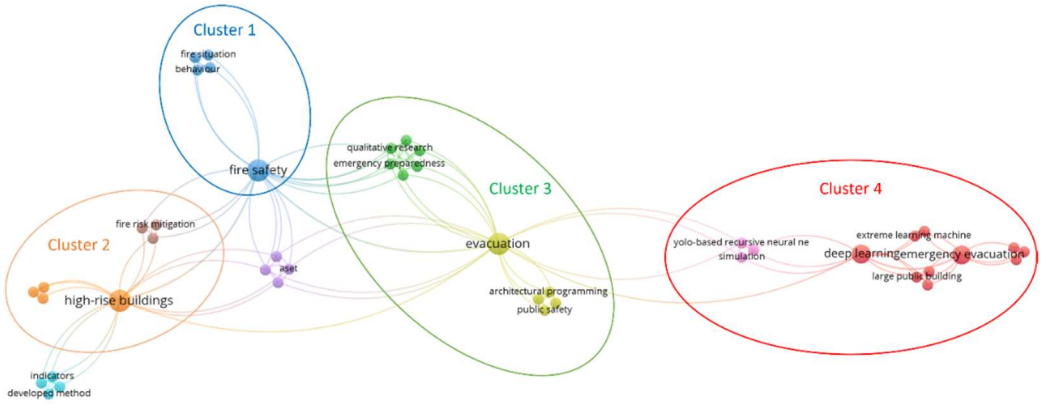

Figure 6: Network Visualization of Co-Occurrences Analysis of Author Keywords

4.2 Building Type

The SLR examined all documented protocols reported in prior studies. Figure 7 presents the distribution of building types investigated in the 25 selected studies on ESRA in high-rise buildings. The review identified six categories of building types across the analyzed articles. Among these, residential buildings were the most frequently studied, with 10 articles. This was followed by office buildings and stadiums or arenas, each represented in four articles. Studies on general high-rise buildings also accounted for four articles, while medical facilities were examined in two studies. Finally, commercial complexes and educational buildings received the least attention, with only one article focusing on this building type. This distribution suggests that research has primarily emphasized residential evacuation scenarios, whereas commercial, medical, and educational building contexts remain relatively underexplored, indicating potential gaps for future investigation. This imbalance indicates a research bias toward common occupancy types, while complex and high-risk environments such as hospitals and educational institutions remain insufficiently explored, despite their unique evacuation challenges and vulnerability profiles.

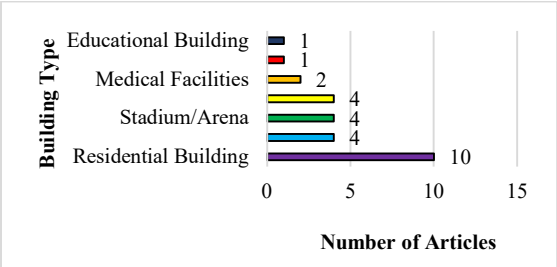

Figure 7: Frequency of Each Building Type in ESRA

Based on the seven building types mentioned, the reviewed studies on ESRA in high-rise buildings encompassed contributions from 10 different countries. Figure 8 present the proportional distribution of these countries, together with the number of studies originating from each. The predominance of research is evident in China, which accounts for 11 studies, representing 44% of the total corpus, thereby constituting the majority share. India accounts for three studies, representing 12% of the corpus. This is followed by Malaysia, Nigeria, and South Korea, each contributing two studies, corresponding to 8% of the overall distribution per country. Finally, the remaining five countries, Chile, Colombia, the United Kingdom, the United States of America, and Vietnam, are represented by a single study each, amounting to 4 % of the total distribution per country.

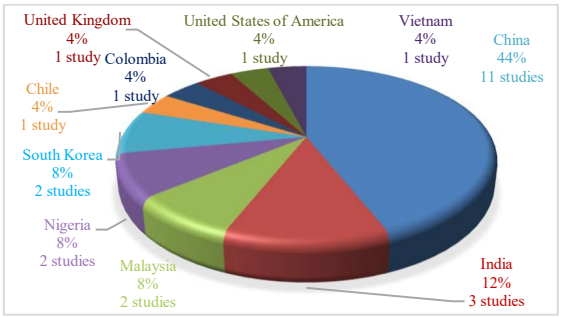

Figure 8: Percentage Country Based on Reviewed Studies of ESRA in High-Rise Buildings

4.3 Technology and Smart System

Figure 9 presents the distribution of technology and smart system applications identified across the reviewed studies. The findings indicate that Pathfinder was the most frequently utilized tool, applied in eight studies [23], [30], [32], [37], [38],

[39], [44], [46]. This is followed by BIM/GIS disaster platforms, represented in seven studies [24], [36], [38], [40], [41], [44], [45] and behavioral analysis models, which appeared in six studies [27], [28], [31], [33], [35], [46]. Other technologies included the Internet of Things (IoT) [25], [29], [42], [47] and decision-making systems [34], [36], [44], [46], each employed in four studies, while Fire Dynamics Simulator (FDS) [37], [40], [41], PyroSim [37], [40], [41], and seismic modeling [26], [27], [30] were the least represented, appearing in three studies each.

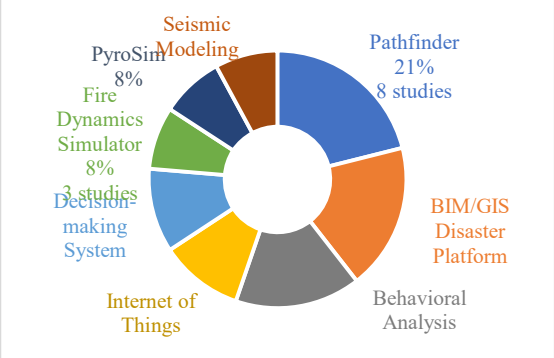

Figure 9: Percentage Technology and Smart System of ESRA in High-Rise Building

The distribution of technological applications demonstrates that simulation-based tools such as Pathfinder and BIM/GIS platforms dominate ESRA research in high-rise buildings, reflecting a strong preference for evacuation modeling and hazard visualization methods. However, comparatively fewer studies incorporated real-time systems such as IoT or advanced decision-support mechanisms, which are critical for dynamic risk assessment during actual emergencies. This imbalance suggests that while simulation tools provide high levels of predictive control, they may lack responsiveness to real-time uncertainties, thereby limiting their operational applicability in real-world evacuation scenarios.

Seven categories of technology and smart systems were identified from the reviewed articles. The most frequently applied tool was Pathfinder, which appeared in eight studies and accounted for 21% of the total. This was followed by BIM/GIS disaster platforms, representing 18%, and behavioral analysis models, which accounted for 16% of the reviewed studies. IoT and decision-making systems each represented 11% of the total, while FDS, PyroSim, and seismic modeling were applied with equal frequency, each contributing 8% to the overall distribution. This distribution highlights the predominance of simulation-based and modeling technologies in ESRA for high-rise buildings, reflecting the field's strong reliance on controlled computational environments. While these tools provide valuable predictive insights, their dominance also reveals a limitation in adapting to real-time and dynamic emergency conditions. The relatively low adoption of IoT and decision-support systems suggests that ESRA research has yet to fully transition toward intelligent, real-time risk assessment frameworks. This gap underscores the need for integrating adaptive technologies that can enhance situational awareness and decision-making during actual evacuation scenarios.

4.4 Evacuation Strategies

As the selected studies were conducted under different contexts, the evacuation strategies employed in each study varied accordingly. Even when the same strategies were adopted, such as vertical and horizontal evacuation, phased evacuation, or total evacuation, the implementation and focus of the studies remained relatively distinct. Table 4 presents the evacuation strategies applied in enhancing ESRA in high-rise buildings, based on the 25 articles that were analyzed.

Table 4: Total Articles for Each of Evacuation Strategies in the Previous Works.

Evacuation Strategies	Number of Articles
Vertical and horizontal evacuation (Stairs, elevators, shafts)	20
Policy/management-led evacuation (Training, drills, manager roles)	8
Behavior-driven evacuation	6
Total/simultaneous evacuation	6
Phased evacuation	5
Inclusivity-focused Evacuation	4

The most widely applied strategy was vertical and horizontal evacuation (stairs, elevators, shafts), which appeared in 20 articles [22], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [39], [40], [41], [42], [43]. These studies consistently demonstrated that stairs remain the dominant evacuation route, while elevators and shafts are increasingly considered to address high occupant density and vertical height limitations. For instance, [37] assessed the role of electrical shafts in residential high-rises, while [42] evaluated a novel elevator-type evacuation device with biomechanical testing on elderly and young populations. However, despite the widespread recognition of vertical evacuation as a baseline approach, the reliance on

conventional stairs reveals a persistent limitation, as many studies fail to adequately address the challenges posed to vulnerable populations and the constraints of extremely tall structures.

Policy and management-led evacuation strategies were identified in eight studies [28], [31], [32], [33], [34], [35], [37], [44]. These emphasized the influence of fire drills, training, and the roles of building safety managers in shaping evacuation outcomes. For example, [28] compared safety managers' perspectives with those of occupants, while [34] highlighted the management of older adults in Indian residential high-rises. These findings underline the critical role of organizational preparedness; nevertheless, the scattered adoption of management-based strategies across the literature indicates that practical implementation often lags behind theoretical recommendations, especially in low- and middle-income contexts. Furthermore, behavior-driven evacuation, focusing on risk perception, alarm response, and decision-making, was evident in six studies [22], [31], [32], [33], [35], [43]. These works demonstrated that human factors such as pre-evacuation delay, perception of alarms, and knowledge of fire safety procedures critically influence evacuation performance. Such findings affirm the well-established observation that human behavior, rather than structural failure, often dictates survival outcomes in emergencies. Thus far, the relatively low number of studies centered explicitly on behavioral responses suggests an underrepresentation of this dimension, despite its proven importance.

Next, total or simultaneous evacuation was also reported in six studies [23], [32], [38], [39], [44], [46]. These studies, often simulation-based, were used to assess congestion levels, exit capacity, and the comparative performance of total versus phased approaches. While total evacuation remains a useful baseline scenario for modeling, evidence from these studies suggests that simultaneous egress in tall and high-density buildings is impractical and potentially unsafe, underscoring the need for hybrid or adaptive evacuation models. Besides that, phased evacuation strategies were documented in five studies [33], [38], [39], [41], [45], where occupants were evacuated in a staged manner to minimize congestion. For instance, [39] optimized phased evacuation in office high-rises, while [41] combined phased stair-elevator strategies incorporating refuge floors in a commercial complex. Phased evacuation is increasingly advocated in tall and complex buildings. However, the small proportion of studies indicates that its practical feasibility remains underexplored, particularly in developing countries where regulatory frameworks are less mature.

Finally, inclusivity-focused evacuation, which addressed the needs of vulnerable populations such as the elderly and mobility-impaired, was identified in four studies [28], [34], [35], [42]. These emphasized accessibility, inclusivity, and tailored evacuation planning. For instance, a study by [42] measured the physical demands of using a lightweight evacuation elevator for both elderly and young participants. The limited presence of inclusivity-focused research highlights a critical gap: despite global demographic trends toward aging populations, most ESRA studies continue to adopt a one-size-fits-all approach, failing to address the disproportionate risks faced by vulnerable occupants.

Overall, the analysis of evacuation strategies reveals a strong reliance on conventional approaches, particularly stair-based evacuation, which may not be sufficient for increasingly tall and densely populated buildings. Although alternative strategies such as phased and inclusivity-focused evacuation have been explored, their limited adoption indicates a gap between theoretical development and practical implementation. This suggests that current ESRA research tends to prioritize feasibility within simulation environments rather than addressing the operational complexities of real-world evacuation, highlighting the need for more adaptive and context-aware evacuation frameworks.

4.5 Methods Used

Several methods were investigated in the studies reviewed in this SLR, demonstrating substantial methodological diversity across analytical, simulation-based, and intelligent computational approaches. Commonly applied techniques included multiple and logistic regression for predictive and behavioral analysis [22], [23], [28], [31], Monte Carlo simulation for uncertainty quantification [23], [45], and agent-based modeling for representing occupant movement and interaction during evacuation [23], [32], [37], [44], [46]. In addition, multi-criteria decision-making frameworks such as the Analytic Hierarchy Process (AHP) and fuzzy comprehensive evaluation were employed for risk prioritization and assessment [32] [30], while advanced algorithms including YOLOv5 and the Dijkstra shortest-path method supported fire detection and optimal route identification [43], [46].

Engineering-oriented studies further incorporated numerical modeling techniques such as Computational Fluid Dynamics (CFD), Finite Element Method (FEM), and Fire Dynamics Simulator (FDS) to simulate fire behavior, structural response, and evacuation conditions [26], [30], [37], collectively illustrating the breadth of quantitative and computational strategies adopted in ESRA research.

Despite shared methodological labels, individual techniques were applied with distinct objectives across studies. Multiple Linear Regression was used both to optimize evacuation performance based on simulated behavioral and architectural variables [23] and to analyze real-world survey data linking demographic and environmental factors to fire safety awareness and risk perception [28]. Logistic regression similarly supported simulation-based prediction of evacuation decisions under controlled fire scenarios [22] as well as empirical analysis of occupants' responses to alarms using survey data [31]. Monte Carlo methods were applied to model uncertainty in evacuation outcomes within agent-based simulations [23] and to generate probabilistic indoor localization datasets for real-time evacuation navigation frameworks [45]. Deep learning approaches, though limited in number, included YOLOv5 for electrical fire detection and movement tracking, sometimes integrated with Recurrent Neural Networks to enhance temporal continuity in evacuation behavior modeling [43], while Convolutional Neural Networks were used to classify evacuation risk levels from simulation-derived density data [46]. Agent-based modeling remained the most frequently adopted approach, with studies differing in emphasis on evacuation optimization [23], demographic-specific behavior [32], critical escape pathways [37], and the generation of training data for learning-based risk assessment models [44], [46].

Multi-criteria and numerical modeling techniques further highlighted methodological variation. AHP was implemented within evacuation simulations to weight urgency levels and vulnerability factors [32] and within expert-driven assessments to prioritize fire safety risks and mitigation strategies for older adults [34], often in combination with fuzzy logic to address uncertainty in human judgment [32], [34]. FEM was employed across different analytical scales, ranging from structural seismic performance of high-rise facilities [30] to multiphysical modeling of geotechnical instability and landslide susceptibility [26], underscoring its versatility. More specialized methods, such as the Levenberg-Marquardt algorithm, were applied for nonlinear optimization tasks including fragility curve fitting for seismic vulnerability analysis [27]. Learning-based models such as Recurrent Neural Networks supported real-time evacuation navigation and movement prediction [43], [45], while Deep Extreme Learning Machine was used for rapid evacuation risk prediction using simulation-generated data [44].

Overall, the reviewed studies demonstrate considerable analytical sophistication and methodological diversity; however, this diversity is accompanied by a lack of integration across approaches. Most methods are applied in isolation, focusing either on physical simulation accuracy or behavioral prediction, but rarely achieving a balance between the two. This separation limits the ability of ESRA models to capture the full complexity of evacuation scenarios, where human behavior, environmental conditions, and system dynamics interact simultaneously. Furthermore, the heavy reliance on simulation-based and deterministic models raises concerns regarding their external validity, as real-world emergencies are inherently uncertain and dynamic. Therefore, future ESRA research must emphasize hybrid and integrative methodologies that combine computational efficiency with behavioral realism and real-time adaptability.

4.6 Outcome from the Systematic Review

As stated earlier, the primary objective of this study is to conduct a systematic review to critically examine the enhancement of ESRA in high-rise buildings. This review concentrated on four main factors: (i) building type, (ii) technology and smart system, (iii) evacuation strategies used to model or analyze evacuation, and (iv) the methodology used. These factors were identified through the review of 25 systematically selected articles. The articles were retrieved based on the inclusion criteria that focused on ESRA in high-rise buildings from 2020 to September 2025. The main databases used were Scopus, WoS, and SD, with GS as a supporting database.

The SLR recognized seven building types represented in the reviewed studies: residential high-rise buildings, office buildings, stadium or arenas, general high-rise buildings, medical facilities, commercial complexes, and educational buildings. From these building types, the geographical distribution of the studies could also be identified. A

total of ten countries were represented. China contributed eleven studies, making it the dominant contributor. India contributed three studies, while Malaysia, Nigeria, and South Korea each contributed two studies. Chile contributed one study, Colombia contributed one study, and the United Kingdom, the United States of America, and Vietnam each contributed one study. While China dominated the sample, the overall distribution indicates a lack of balance, with a concentration of studies in a small number of countries and limited representation from other regions.

This SLR further examined the technologies and smart systems applied in the reviewed studies, which demonstrated a variety of approaches to modeling and enhancing ESRA in high-rise buildings. Among the 25 studies, Pathfinder was the most frequently used tool, appearing in eight studies, primarily for evacuation simulation and performance evaluation. BIM/GIS disaster platforms were employed in seven studies, and behavioral analysis appeared in six studies, reflecting the increasing reliance on integrated spatial modeling and human-centered analysis for evacuation safety. IoT and decision-making systems each appeared in four studies. FDS, PyroSim, and seismic modeling each appeared in three studies, indicating their growing but still limited role in high-rise safety assessments. Collectively, these findings reveal that simulation platforms such as Pathfinder and BIM or GIS dominate the ESRA literature, while emerging technologies such as IoT and advanced decision-making systems remain underutilized despite their potential to transform evacuation safety in high-rise contexts.

In terms of evacuation strategies, the review identified several main approaches. The most frequently studied was vertical and horizontal evacuation using stairs, elevators, and shafts, which appeared in 20 of the studies. Policy and management-led evacuation (training, drills, and the role of safety managers) was emphasized in eight studies, behavior-driven evacuation in six studies, total or simultaneous evacuation in six studies, phased evacuation in five studies, and inclusivity-focused evacuation in four studies. These findings illustrate that simulation-based evacuation remains central in ESRA studies of high-rise buildings, while hybrid strategies and adaptive approaches are only beginning to emerge.

Finally, this review analyzed the methods used in the studies. The most frequently applied approach was Agent-Based Modeling, which appeared in six studies, followed by Multiple Linear Regression, Logistic Regression, Monte Carlo, YOLOv5, Analytic Hierarchy Process, Fuzzy Comprehensive Evaluation, Finite Element Method, Convolutional Neural Network, and Recurrent Neural Network, each appearing in two studies. Beyond these, the Levenberg–Marquardt algorithm and the Deep Extreme Learning Machine were each used in one study, applied for curve fitting, model optimization, or advanced pattern learning. Collectively, these findings show that while the computational landscape of the studies was diverse, the field remains heavily reliant on deterministic and simulation-driven algorithms, with limited adoption of learning-based or adaptive intelligent algorithms that could enhance the realism and predictive accuracy of fire and evacuation modeling. Overall, this SLR demonstrates that research on ESRA in high-rise buildings is expanding across multiple building types and strategies, but remains unevenly distributed in terms of geography and methodology.

4.7 Gaps and Future Research Direction

Recognizing limitations is critical in ensuring the integrity and transparency of this review. In this context, several limitations of the present study should be acknowledged. First, the SLR was restricted to three major databases, namely Scopus, WoS, and SD, which may have excluded relevant studies from other sources and introduced selection bias. Second, the time frame of 2020 to 2025, while capturing recent developments, may have omitted earlier foundational studies that contribute to the theoretical grounding of ESRA. Third, the inclusion criteria focused solely on peer-reviewed journal articles, thereby excluding conference papers and industry reports that may provide practical insights. Additionally, the thematic analysis involves a degree of subjective interpretation during coding and categorization, which may influence the identification of themes. Lastly, the bibliometric analysis is based on keyword co-occurrence, which reflects patterns from metadata rather than the full conceptual depth of the studies. These limitations should be considered when interpreting the findings of this review. By explicitly acknowledging methodological and data-related constraints, the accuracy and reliability of the study are upheld, thereby supporting the continuous development of knowledge in the field of ESRA. Based on the analysis of the selected literature, several research gaps were identified.

Although ESRA is an essential component in advancing the safety of high-rise buildings, the review reveals that certain dimensions remain underexplored. For instance, while numerous studies focus on vertical evacuation using stairwells, far fewer address alternative strategies such as elevator-assisted evacuation, refuge floors, and hybrid approaches that combine phased and total evacuation. In addition, a key limitation evident across the studies is the narrow scope and classification of algorithmic applications. Most research focuses on a single modeling perspective without integrating multiple algorithms or interdisciplinary data streams for holistic scenario analysis. This results in computational models that are typically optimized for either physical accuracy or behavioral prediction, but seldom both, leading to gaps in interpretability, adaptability, and real-world applicability. Behavioral dimensions, including pre-evacuation delay, cultural influences, and group dynamics, are also insufficiently represented compared to simulation and technological modeling. Due to database restrictions, the review relied on a limited range of sources, including Scopus, WoS, and SD, which may have excluded relevant studies published in regional journals or other specialized databases. Moreover, the identified studies still employed simulation-based methods, such as Pathfinder, PyroSim, FDS, while empirical, field-based, and experimental investigations remain scarce. This methodological imbalance restricts a more holistic understanding of real-world evacuation behaviors.

To address these gaps, several recommendations for future research are proposed. First, further studies should investigate the comparative effectiveness of phased, total, and hybrid evacuation strategies, particularly in super high-rise and mixed-use buildings. Second, there is a need for greater emphasis on inclusivity by examining the evacuation needs of vulnerable groups and integrating universal design principles into evacuation models. Third, future research should expand its methodological diversity, complementing simulation-based approaches with empirical studies, drills, and human-centered experiments. Lastly, future SLRs should incorporate a wider range of databases and alternative search strategies such as citation tracking, snowballing, and expert consultation, to ensure comprehensive coverage of the rapidly evolving ESRA literature.

4.8 Research Contribution

This SLR provides a comprehensive analysis of current trends in ESRA in high-rise buildings, with emphasis on four critical dimensions: building type, technology and smart systems, evacuation strategies, and methods used. The review identifies significant patterns by synthesizing research across diverse types of buildings, including residential buildings, office buildings, commercial complexes, medical facilities, stadiums or arenas, and general high-rise buildings. The findings highlight the methodological approaches and tools employed in ESRA, as well as the rationale underpinning their application in high-rise contexts. In contrast to earlier reviews that predominantly focused on a single disciplinary perspective or a narrow set of methodologies, this study offers a broader, integrative outlook that uncovers limitations such as building context bias, methodological fragmentation, and insufficient attention to cross-domain integration. The outcomes of this review provide researchers, practitioners, and policymakers with actionable insights and recommendations to enhance the scalability, robustness, and reliability of ESRA methods for high-rise buildings. Moreover, synthesis advances the theoretical and practical understanding of evacuation safety by charting a structured research agenda that addresses existing challenges and promotes interdisciplinary collaboration. In doing so, this SLR makes a substantial contribution to the advancement of ESRA practice and awareness, ultimately supporting the development of safer and more resilient high-rise environments.

4.9 Differences from Prior Work and Study Achievement

In contrast to prior studies on evacuation safety risk assessment (ESRA), this study provides a more comprehensive and critically integrated perspective on research trends in high-rise buildings. Existing literature reviews in this domain have often focused on specific aspects such as fire safety modeling, evacuation simulation, or behavioral analysis in isolation. As a result, these studies offer limited insight into how different methodological, technological, and strategic components interact within the broader ESRA framework.

Furthermore, many previous reviews adopt a descriptive approach, primarily summarizing findings without critically evaluating the limitations, interconnections, and practical implications of the reviewed studies. In contrast, this study adopts a critical analytical approach that not only synthesizes

existing research but also evaluates methodological gaps, identifies structural fragmentation, and highlights the imbalance between simulation-based methods and real-world applicability.

Another key distinction lies in the integration of bibliometric mapping with systematic literature review. While prior studies typically rely on either qualitative synthesis or quantitative bibliometric analysis independently, this study combines both approaches to provide a deeper understanding of the intellectual structure and emerging trends in ESRA research. This integration enables the identification of hidden relationships between research themes, offering insights that are not readily observable through conventional review methods.

In addressing the need for a more holistic and structured understanding of ESRA, this study achieves several contributions. It systematically classifies research into four major themes, reveals the dominance of simulation-based approaches, and identifies critical gaps such as the underutilization of artificial intelligence, limited integration of behavioral factors, and lack of real-time adaptive systems. These findings provide a clearer direction for future research and contribute to the development of more integrated, data-driven, and practically applicable ESRA frameworks for high-rise buildings.

5. CONCLUSION

The primary objective of this study is to conduct a systematic evaluation of ESRA in high-rise buildings from 2020 to 2025. Using the PRISMA approach and thematic analysis, we systematically reviewed 25 selected publications. In addition, bibliometric mapping using VOSviewer was incorporated to visualize keyword co-occurrences that support the findings. The study examined four overarching themes: building type, technology and smart systems, evacuation strategies, and methods used. Within these themes, 33 subthemes were identified, comprising seven subthemes under building type, eight under technology and smart systems, six under evacuation strategies, and 12 under methods used. The review revealed that residential buildings were the most frequently studied building type, while simulation-based tools such as Pathfinder and BIM/GIS disaster platforms dominated the technological approaches. Vertical and horizontal evacuation strategies, particularly involving stairs, elevators, and shafts, emerged as the most extensively examined evacuation methods. In terms of methods used, most studies concentrated on agent-based modeling, with comparatively fewer studies in complex methods, such as Monte Carlo, YOLOv5, CNN, RNN, DELM, and the Levenberg-Marquardt algorithm.

The outcomes of this SLR provide substantial contributions to both practice and scholarship in the domain of ESRA. First, it provides a structured and comprehensive synthesis of ESRA research by integrating four critical dimensions, namely building type, technology and smart systems, evacuation strategies, and methods used, thereby offering a unified perspective that is lacking in existing literature. Second, it advances current understanding by critically identifying key limitations in the field, including methodological fragmentation, over-reliance on simulation-based approaches, and the limited integration of behavioral and real-time adaptive systems. Third, through the combined use of systematic literature review and bibliometric mapping, this study reveals underlying research patterns, thematic relationships, and emerging trends that are not readily observable in conventional reviews. Collectively, these contributions enhance both the theoretical and practical understanding of ESRA and provide a clearer foundation for the development of more integrated, data-driven, and context-aware evacuation safety models for high-rise buildings. Nevertheless, several limitations must be acknowledged. Due to database accessibility constraints, the scope of this review was limited to a selected set of publications, and future research could benefit from incorporating a broader range of databases or exploring different temporal spans.

Ultimately, this study demonstrates that while ESRA research in high-rise buildings has achieved significant progress in simulation and computational modeling, it remains conceptually fragmented and limited in real-world applicability. The dominance of simulation-based approaches, coupled with the underrepresentation of behavioral and real-time adaptive systems, restricts the ability of current models to fully capture the complexity of evacuation scenarios. Therefore, future research must move toward integrative and hybrid frameworks that combine engineering precision, human-centered analysis, and intelligent data-driven technologies. Such an approach is essential for developing more robust, adaptive, and practically relevant evacuation safety solutions in increasingly complex high-rise environments.

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