Fire Safety in single-exit stair residential buildings: a scoping review of published literature

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FIRE SAFETY IN SINGLE-EXIT STAIR RESIDENTIAL BUILDINGS: A SCOPING REVIEW OF PUBLISHED LITERATURE

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Executive Summary

The purpose of this report is to provide information on published scientific literature that may be relevant within the context of major residential buildings with single-exit design. This report presents the findings of a scoping review that assessed the current state of knowledge in scientific literature on egress performance in residential buildings, with a particular focus on buildings designed with a single-exit stairwell. The review was conducted in the context of growing interest in permitting single-exit stair configurations in low- and mid-rise multi-unit residential buildings. While such designs are often proposed as a means to improve affordability and space efficiency, the fire safety and evacuation implications remain underexamined.

The scoping review was conducted using the Joanna Briggs Institute (JBI) methodology and reported in accordance with Preferred Reporting Items for Systematic Reviews and Meta-Analyses - Scoping Reviews (PRISMA-ScR) guidelines. The review focused on factors affecting evacuation performance in residential buildings with single-stair configurations in the scientific literature. Literature was selected across four main areas: passive fire safety measures, active fire detection and suppression systems, evacuation performance under various stair configurations, and validation methods including simulations and probabilistic models. The review included peer-reviewed articles, technical reports, and relevant grey literature without restrictions on publication date or geographic origin. Studies were sourced from major databases including Scopus, Web of Science, PubMed, and Google Scholar, as well as supplementary sources such as the Society of Fire Protection Engineers (SFPE) Handbook and National Research Council of Canada (NRC) and National Institute of Standards and Technology (NIST) archives. A two-stage screening process was applied using both automated filtering and manual review to ensure relevance, with exclusions for non-residential buildings (except for office buildings from which relevant insights could be drawn), supertall structures, and non-fire-related emergencies.

A total of 194 studies were reviewed, encompassing experimental, numerical, statistical, and review-based methodologies. Only 9% of these studies addressed single-exit stair configurations explicitly, indicating a significant research gap. The literature was categorized into key thematic areas influencing evacuation performance based on the objectives, functional statements and intent of the National Building Code of Canada. These themes include human behaviour and decision-making, occupant characteristics, functional limitations, exit design, evacuation strategies, protection of exit facilities, fire load and behavior, and firefighting operations.

Key findings highlight that:

- Human behaviour, including pre-evacuation delays and route choice, can potentially impact evacuation timelines; however, the specific impact in single-exit stair buildings requires further investigation.

- Demographic diversity, functional limitations, and varying occupant characteristics introduce complexity in evacuation dynamics, which is not sufficiently accounted for in current design standards or models.
- Evacuation strategies such as elevators for egress and Internet of Things (IoT)-based evacuation guidance show promise but require further validation in single-exit contexts.

- Smoke control, door (stair and compartment) operation, and fire load distribution are critical factors that can influence the effectiveness of a single egress route.

- Firefighter access and counterflow interactions in single-exit stair buildings remain understudied and pose potential operational challenges.

The review identifies substantial gaps in the scientific literature, particularly around the impact of occupant load, flow congestion, dynamic behaviours, and comparative studies between single and multiple exit configurations. Additionally, most studies relied on homogeneous participant samples, i.e., primarily young adults without functional limitations, and lacked data-driven modeling approaches.

This report provides a foundation for future research efforts and technical decision-making. It is intended to support discussions about the suitability and safety of single-exit stair designs in residential buildings and to inform the development of fire safety provisions to address these designs. This report acknowledges that, based on available research, it is not possible to draw conclusions about the relative safety of single- versus dual-exit configurations.

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1.0 INTRODUCTION

1.1 OVERVIEW OF STUDY

This report intends to provide information regarding the scientific literature available at the time writing that may be relevant within the context of major residential buildings with single-exit design.

This study was initiated by the National Research Council of Canada (NRC) to gather and understand the state-of-the-art in scientific literature and methodologies, with a specific focus on fire safety and egress in buildings that incorporate a single exit stair. The review has been conducted in the context of recent interest in designing single exit stair configurations in multi-unit residential buildings. Drawing from a wide range of academic and technical literature, the report summarizes key findings, highlights knowledge gaps, and explores the implications of single-exit configurations for occupant safety and emergency response. This report does not assert that the existing literature is sufficient to determine whether single-exit configurations offer a level of safety equivalent to that of dual-exit designs.

1.2 BACKGROUND

Fire remains a primary life safety hazard in residential structures in Canada and the United States [1], [2], [3]. The economic impact of fire-related losses – despite advancements in fire protection and suppression technologies – continues to be significant [1], [4], [5]. Beyond financial losses, fires impose indirect effects on individuals and communities, with the additional potential for loss of life, injuries, or both [6], [7], [8]. On the one hand, the shift toward sustainable building practices suggests the adoption of single-exit stair configurations in mid-rise residential structures [9], [10]. On the other hand, the rationale for the use of these building keeps shifting over time from an economic to increased design flexibility.

Documents such as the Canadian National Model Codes prescribe minimum requirements for means of egress. The means of egress is comprised of three continuous and unobstructed components: an access to an exit, an exit facility (such as doors or stairs), and an exit discharge (such as an exterior door). These components must facilitate continuous and unobstructed movement from any point within the building to the exterior [11]. In multi-storey buildings, exit stairs form a critical part of the means of egress to facilitate egress from floors above the ground floor, and most international building regulations specify the number and design of the exit stairs to allow for unimpeded evacuation [12]. Modern building regulations in many jurisdictions have evolved to require at least two exit stairs from most floor areas, depending on factors such as occupancy, building height, and occupant load, except in specific conditions where a single-exit stair is permitted, although these conditions vary across international building codes. For example, in Canada, the National Building Code (NBC) [11] currently allows single means of egress in residential occupancies for up to 6 metres (two storeys). Similarly, in the United States of America (USA), the International Building Code (IBC) allows for single means of egress configuration up to 9 metres (three storeys) [13]. Other model codes, such as the National Fire Protection Association (NFPA) 5000 “Building Construction and Safety Code” permit up to four storeys of apartments with a single

stairwell [14], while cities like Honolulu, New York, and Seattle allow point access blocks up to six storeys under additional fire safety measures [9]. This contrasts with other developed countries such as the United Kingdom (18 metres) [15], Australia (less than or equal to 25 metres) [16], France (50 metres), and China (54 metres) [9], [17]. It is important to highlight that in most codes the thresholds allowing for a single means of egress depend not only on the building's height but also on other factors including the occupant load, the exit access travel distance, and whether the building is equipped with a fire sprinkler system.

In North America, there has been a recent push to introduce the construction of single-exit stair multi-storey residential buildings with increased heights as a means to meet affordable housing demands in urban areas [19]. However, the economic benefits are currently (as of the date of this report) hypothetical, stemming from proposals that single-exit stair residential buildings can reduce footprints and maximize unit space [20], [21], [22], [23]. Further, the implications of single-exit stair designs on evacuation performance and building fire safety have not been studied extensively [17].

Other aspects relevant to single-egress designs have been researched more widely, however. For instance, various studies have examined stair geometric features, including width, length, location, and slope [25], [26], [27]. Research has also highlighted the limitations of stairs as a means of egress for individuals with functional limitations, particularly mobility-related disabilities [28]. Other studies have explored physical and psychological factors influencing stairway evacuation, such as fatigue and biomechanics [29], [30], [31], merging of evacuation streams [32], social dynamics and evacuation behaviour [33], [34], [35], effect of obstacles on egress routes [36], and considerations associated with opposed pedestrian flows in staircases (ingress/egress) and firefighting techniques [37], [38], [39], [40], [41]. The performance of egress systems, including stairs, has been analyzed using concepts such as available safe egress time (ASET) versus required safe egress time (RSET) [42], numerical modeling [43], [44], fire safety drills [45], and fire incidents [46]. Despite extensive research, the primary focus remains on exit-stair geometric design to facilitate evacuation, with limited attention to evaluating performance of exit stairs based on their number (redundancy) and location in a building.

1.3 PURPOSE AND SCOPE OF REPORT

Therefore, the purpose of this study is to carry out a scoping review to identify available research that could provide a basis for future research on the topic of single-exit stair configurations in multi-unit residential buildings.

Specific objectives of the study are to:

1. Provide an overview of the body of the scientific knowledge relevant to the discussion on single-exit stair configurations in multi-unit residential buildings.
2. Identify trends, available data and gaps in the scientific literature that require further evaluation.

The scope is limited to residential buildings although insights are drawn from some non-residential buildings such as office and mixed-use buildings where single-exit stair

configurations have been studied. The review is not an evaluation of current building codes or regulatory policies. Additionally, the study does not hypothesize that single means of egress are preferable or undesirable. Rather, the study aims to gather information from the scientific literature to describe the current body of knowledge regarding evacuation performance in residential buildings. Specifically, it will identify concepts, trends, and gaps related to single-exit stair strategies and their potential implications, thereby providing an overview of the current status quo. The assessment is intended to guide the development of research programs that can inform any changes in Canadian codes related to single-exit stair designs in buildings.

1.4 2020 NATIONAL BUILDING CODE OF CANADA SINGLE-EXIT REQUIREMENTS

In this report, evacuation in single-exit stair buildings is studied in the context of the NBC [11] requirements for exiting from buildings. Note, however, that this section is not intended to serve as a detailed review of the NBC and is purely intended to provide the reader with context. The NBC is an objective-based code with a framework of objectives, sub-objectives and functional statements, developed through a bottom-up analysis of the existing requirements called acceptable solutions. The objectives are high level and qualitative, covering general concepts of the Building Code such as "Fire Safety." The sub-objectives and functional statements further detail what the Building Code is trying to achieve with respect to the protection of occupants and property.

The number of exits required from floor areas are prescribed by the following acceptable solution of the building code:

NBC Division B, Part 3, Sentence 3.4.2.1.(1) Minimum Number of Exits
Except as permitted by Sentences (2) to (4), every floor area intended for occupancy shall be served by at least 2 exits[1]

The objective and functional statements of Sentence 3.4.2.1.(1) are listed below:

Table 1: Functional Statement and Objectives.

Acceptable Solution	Functional Statements	Objectives
3.4.2.1.(1)	F05, F06, F10, F12	OS3.7
	F06, F12	OS1.2
	F06, F12	OP1.2

In the case of the requirements for the number of exits, the objectives of the NBC are to limit the risk of injury due to hazards to people or property caused by:

OS/OP1.2	Fire or explosion impacting areas beyond its point of origin
OS3.7	Persons being delayed in or impeded from moving to a safe place during an emergency

[1] Sentence 2 to 4 provide specific exemptions that permit single exits in floor areas.

The associated functional statements, which indicate the intended performance of the design, are:

F05	To retard the effects of fire on emergency egress facilities.
F06	To retard the effects of fire on facilities for notification, suppression and emergency response.
F10	To facilitate the timely movement of persons to a safe place in an emergency.
F12	To facilitate emergency response.

In addition, the NBC has intent statements associated with the requirements that provide a plain-language explanation of the requirement to assist in the interpretation of the acceptable solution requirement. The following intent statements are provided relative to the number of exits required and occupant safety:[2]

> *To limit the probability that persons will not have a choice of an alternative exit in the event that one exit is blocked or obstructed in an emergency situation, which could lead to delays in the evacuation or movement of persons to a safe place, which could lead to harm to persons.*
>
> *To limit the probability that emergency responders will not have a choice of an alternative exit in the event that one exit is blocked or obstructed in an emergency situation, which could lead to emergency responders being delayed in gaining access to a floor area, which could lead to delays or ineffectiveness in emergency response operations, which could lead to delays in the evacuation or movement of persons to a safe place, which could lead to harm to persons.*

[2] National Building Code of Canada 2015 – Intent Statements | National Research Council Canada

2.0 LITERATURE REVIEW METHODOLOGY

An effort was made to cover a wide spectrum of materials dealing with the problem of emergency egress from buildings, and as such, a scoping review approach was selected as a suitable methodology to review egress literature more broadly. The primary research questions guiding this study were:

- How is evacuation performance assessed in current building fire safety design?
- What are the implications of single-exit stair designs on evacuation performance?
- What research gaps exist concerning fire safety of single-exit stair designs or how evacuation performance is being evaluated?

The literature review methodology consisted of three phases as follows:

1. Characterizing evacuation performance relative to the egress requirements of the NBC to determine relevant factors/themes that may influence evacuation in single-exit stair buildings.
2. Conducting a literature search in accordance with the Joanna Briggs Institute (JBI) [50] methodology for scoping reviews and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses - Scoping Reviews PRISMA-ScR method [51].
3. Analyzing the literature relative to the study characteristics and relevance of study findings to evacuation in single-exit stair buildings. The analysis involved classification of the studies based on categorized factors, extraction of relevant findings and identifying research gaps.

The review methodology is discussed further in the following sections.

2.1 CHARACTERIZING EVACUATION PERFORMANCE

As outlined in Section 1.4, the stated objectives of the NBC indicate that evacuation performance is considered a function of the fire and its effects, the building system response, and the human response. The human response includes factors such as the evacuating occupants' behaviour and physical characteristics, the occupants' movement and firefighters' response, whereas the fire characteristics include its size, location and behaviour. The building system response may include fire protection systems, the design and protection of exit facilities, as well as the notification and communication of the fire emergency to occupants. Therefore, to better understand the impact of single-exit stair designs, a more holistic understanding of evacuation performance is sought in scientific literature in the context of these factors.

To do so, the fire, building system, and human response factors are further subdivided into categories based on the objectives, functional statements, and intent statements of the NBC. The categories are summarized as follows:

- Exit Redundancy (ER): Focuses on the number and location of exit stairs specifically.

- Human Behaviour and Decision Making (HBD): Focuses on behavioural and decision-making aspects of building occupants in relation to fire emergencies (e.g., studies assessing occupants' pre-movement, response to alarms and other factors that may delay or enhance evacuation).
- Occupant Characteristics (OC) and Demographic Effects (D): Encompasses occupant physical traits or factors affecting them physically (e.g., studies analyzing walking speeds under different evacuation conditions or those related to ergonomics). Demographics include variations in population characteristics such as age, gender, or disability status.
- Occupant Loads (OL).
- Exit Design (ED): Focuses on the effects of geometric variations in exit widths, lighting, and signage.
- Evacuation Flows (EF): Discusses the effects of merging flows or counter flows.
- Evacuation Time (ET).
- Communication during Evacuation (CE): Includes the effects of alarms, notifications, and signage.
- Evacuation Strategies (ES): Focuses on the effects of different types of strategies, such as simultaneous evacuation, phased evacuation, stay-put strategies and the use of refuges or elevators as escape routes.
- Protection of Exit Facilities (P): Covers studies focusing on active or passive fire safety measures such as compartmentation, stair pressurization, sprinklers, and smoke control.
- Fire Load and Fire Behaviour (FLB): Encompasses the effects of fire location, fire size, or any parameter related to fire dynamics.
- Fire Fighters' Response (FFR): Focuses on fire fighter operations in a building fire, and the effects of counterflows with evacuating occupants.

The following sections present the literature search procedure and the extraction and analysis of data in the context of the factors listed above.

2.2 LITERATURE SEARCH PROCEDURE

The scoping review was conducted in accordance with the JBI [50] methodology for scoping reviews while reporting following Preferred Reporting Items for Systematic Reviews and Meta-Analyses – Scoping Reviews PRISMA-ScR method [51] of presentation. The scoping review focuses on factors influencing evacuation performance in residential buildings with single-stair configurations. Literature identified as appropriate to the objectives of the study was generally clustered among the following main areas of interest:

- Fire Safety Passive Measures: Compartmentation, smoke management, exit-stair and corridor design, wayfinding/signage, and accessibility for individuals with disabilities.
- Fire Detection and Suppression: Systems such as sprinklers, detectors, and alarms aimed at fire control and occupant safety.

- Quantification of evacuation performance under different stair configurations (single vs. multiple), including firefighter access and movement.
- Validation Methods and Performance Measurements: This review includes studies utilizing – but not limited to – numerical simulations, representative fire scenarios, failure assessment models, and probabilistic approaches to quantify evacuation performance and evaluate fire safety strategies.

Studies focused on technology development, and code compliance assessments for passive or active fire safety measures were excluded. The focus is on residential buildings; however, relevant insights are drawn from office buildings. The search was not restricted based on building height, although skyscrapers, single-family dwellings, detached houses, and other non-residential occupancies (other than office buildings) were excluded. There were no geographic limitations. Studies from any country were considered to provide a global perspective. There were no restrictions on the date of publication to ensure comprehensive coverage of literature, reflecting both historical and current perspectives.

The review includes journal articles, conference proceedings, books, and grey literature (technical reports, model codes, provincial codes, and standards), excluding dissertations and unpublished reports. For the purposes of this review, no distinction was made between original studies and review documents. Each publication was treated as an individual unit of analysis.

The following databases were included: Scopus and Web of Science, as they represent the largest repositories of scientific literature. PubMed was also included to capture studies related to psychology, specifically ones related to human behaviour. Additionally, Google Scholar was incorporated to account for any literature that might have been overlooked.

Supplementary data was sourced from the Society of Fire Protection Engineers (SFPE) Handbook of Fire Protection Engineering, 5th Edition [52], the Collective Dynamics Journal (which is not indexed by Scopus but contains peer reviewed studies related to human mobility), the NRC Publications Archive, and the National Institute of Standards and Technology (NIST) publications database.

Table 2 outlines the search strings applied to each database, including exclusion keywords. Notably, Scopus was queried with two distinct search strings. An initial search using "Fire AND Safety AND Residential AND Building" missed critical studies on evacuation, prompting a secondary search in Scopus explicitly incorporating the term "evacuation."

Table 2[3]: List of databases, search strings and exclusion keywords used to search the body of knowledge.

Database	Search string	Exclusion keywords
Scopus	fire* AND (evac* OR egress) AND build*	Earthquake, wildfire, explosion, market, storage,

[3] For databases where exclusion keywords are identical, the table references the initial database to avoid redundancy.

		settlement*, tsunami, air*, disaster, climate, algorithm, mining, school*, hospital, ship, nursing, industrial, tall, supertall, library, museum, factory, underground, transit, warehouse, chimney, plant, outdoor, tunnel, Subway, ohs, substation, house*, concrete, forest, shooter, steel, big data
Scopus	"Fire" AND "safety" AND "residential" AND "building"	Earthquakes, wildfire, tsunami, shooter, houses, single family dwelling, care homes, public health, injury, fire prevention, chimneys, urban risk
Google Scholar	"Fire safety"" AND "residential building"	Same as Scopus (second row)
Web of Science	"Fire" AND "safety" AND "residential" AND "building"	Same as Scopus (second row)
PubMed	"Fire" AND "safety" AND "residential" AND "building"	Same as Scopus (second row)
NRC-CNRC	"Fire" AND "residential" AND "building"	Same as Scopus (second row)

The PRISMA-ScR diagram in Figure 1 illustrates the search results generated. First, the search string, followed by the refined results after applying exclusion keywords. Exclusion keywords were selected to filter out studies focusing on evacuation due to earthquakes, non-residential buildings (except office buildings which were included), super tall structures, small, detached structures, facades, and urban-level fires. The initial filtering phase targeted titles, abstracts, and keywords.

A second phase involved manual screening of full texts, applying exclusion criteria listed in

Table 3. This process involved sequential exclusions. If a study met an exclusion condition (e.g., non-residential focus), it was removed from consideration at that stage. Duplicate records were eliminated after this phase.

Table 3: Manual screening process involving a sequential set of exclusion criteria/questions applied in order.

Manual Screening Criteria
Study does NOT address residential, mixed use or office buildings, or provide relevant insights applicable to residential buildings.
Is the study out of scope or does the paper only address specialty topics, e.g., structural fire resistance, non-conventional buildings materials, special structures (such as container buildings), urban fire risk, sprinkler system design, fire water supply, combustible facades, i.e., no holistic fire safety scope?
Paper only addresses compliance, fire safety public education or fire prevention.
If the study uses statistical/numerical methodology, is there is an experimental validation? If not, is their obvious uncertainty when it comes to validation or verification of the results?
Unavailable through Carleton University, or NRC sources.

Mendeley software [53], which is a reference management software that organizes research papers and other types of documents, supports citation and bibliography creation. It was used in the initial screening and duplicates removal, while Microsoft Excel was employed for manual filtration and subsequent classification and organization of included documents. Screening and source selection were conducted by the first two authors, with cross-checking performed by other authors on a random subset of manually filtered results.

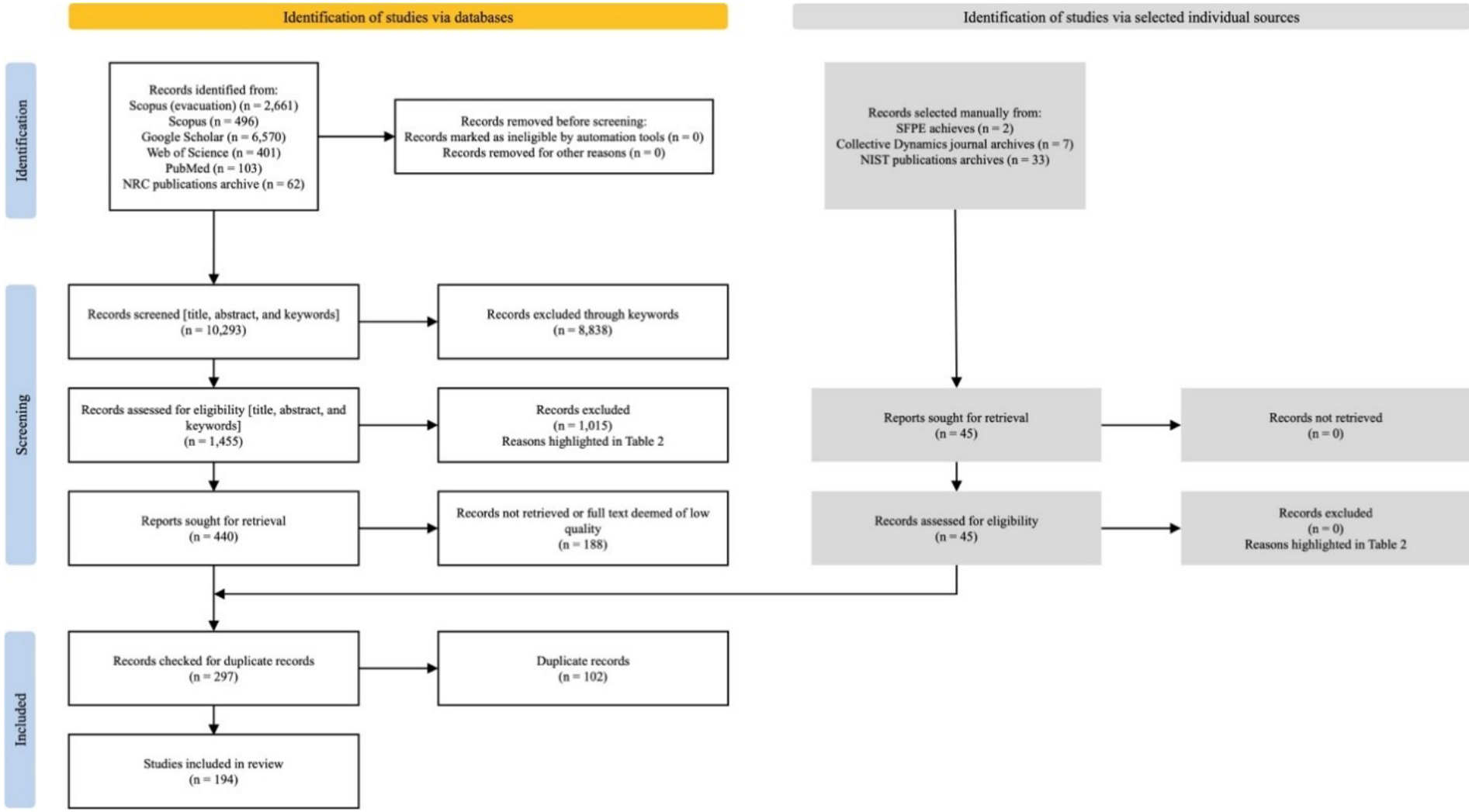

Figure 1: PRISMA2020 flowchart of the scoping review

2.3 DATA EXTRACTION AND METHOD OF CRITIQUE

Data from eligible studies were extracted using a standardized form developed in Microsoft Excel. The form was piloted on a sample of studies to ensure it captured relevant information. The following particulars were extracted: paper classification (journal or conference article), publication year, country of origin, building occupancy, internal classification based on the study-identified theme, study methodology (i.e., whether the study was numerical or experimental and which software was used if numerical), nature of the data, whether a single means of exit was explicitly focused on wholly or partially, the main findings (including the study's primary objective), the possible impact on single-exit stair configuration (including identification of potential research gaps), any additional factors that might influence evacuation, and study limitations (either explicitly stated by the authors or determined by the reviewers).

Country of origin was determined based on the location of the building studied in an article or the set of regulations the authors stated they followed. If neither was provided, the article was deemed generic. The "nature of data" category included details such as the number and types of experiments (e.g., virtual reality, survey), the number of participants, or, in numerical studies, the number of simulations and the algorithms used.

Two reviewers – the first authors of this work – independently extracted data, with each assigned a set of studies from which to extract the aforementioned information. Both authors cross-checked the data extracted from random articles in the other reviewer's batch. Any discrepancies were discussed and resolved through consensus. Data were extracted and categorized based on study-identified themes according to each study's aim or purpose and highlighting notable strengths, limitations, and research gaps. The categories or themes identified in Section 2.1 of this report were used to classify the studies further.

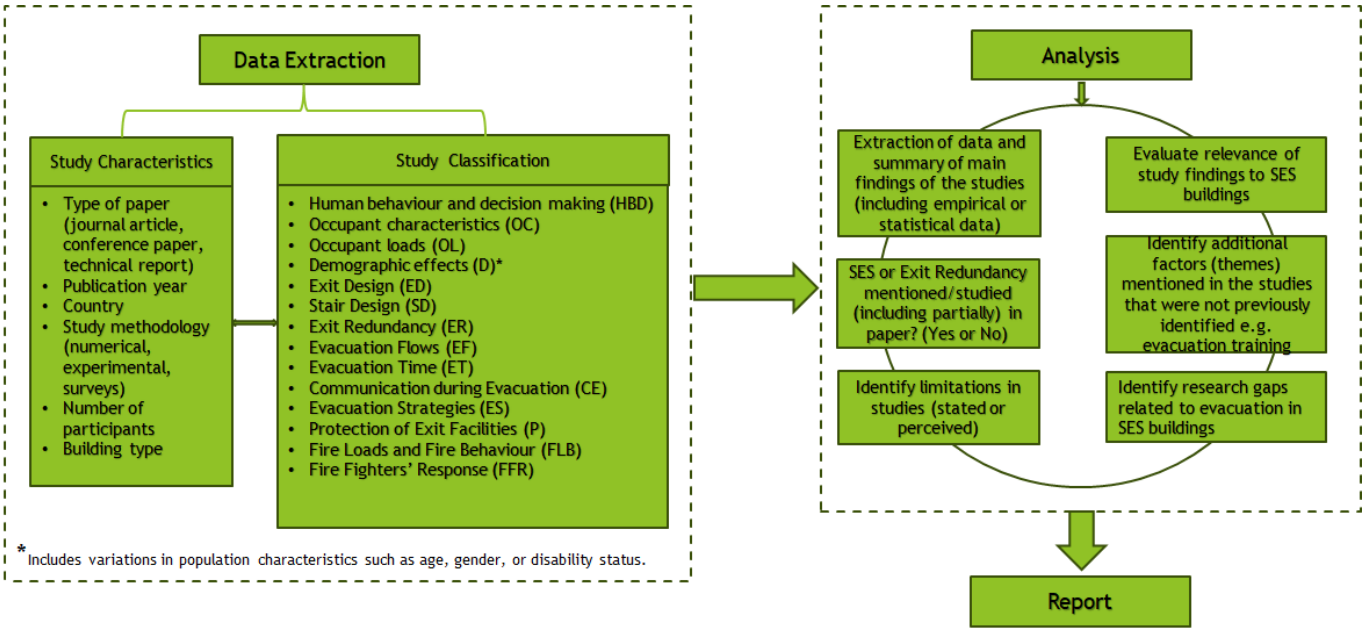

Figure 2: Data extraction and method of critique

This classification allowed for general trends identification. Assigning a theme to a study was based on the individual judgment of the authors. In addition to the thematic classification of studies, methodological approaches were also divided into five main categories: Experimental, Numerical, Mixed (Experimental and Numerical), Literature Reviews, and Statistical i.e., analyzes existing data, e.g., record of interviews with fire incident survivors or summarizing literature on fire loads in office buildings.

Only 71 of the 194 included studies were discussed in detail in the main body of the report, as studies drawing similar conclusions were grouped, and representative examples were selected based on clarity. The full list of included studies is available in the supplementary material.

2.4 LIMITATIONS OF THE REVIEW METHODOLOGY

Several limitations of the presented scoping literature review need to be considered (for limitations of the research studies reviewed, see the previous section). First, although broad keywords were used to ensure inclusivity, some relevant studies may have been excluded due to the constraints of the search strategy. For example, the firefighting operations category may include more studies. The same goes for the protection of exit facility and fire load and fire behaviour category. Second, no formal quality appraisal or weighting of reviewed studies was conducted; instead, the results provide a quantitative overview to contextualize current knowledge and identify future research needs. Third, the categorization of studies is based on a subjective interpretation and emerged organically, as no standardized criteria were applied. Fourth, many reviewed sources were literature reviews, which inherently depend on prior publications that may include methodological inconsistencies, incomplete data, or unverified assumptions. Fifth, there was no focus on particular outcome variables (e.g., comparison between evacuation timing in single vs. multiple exit-stair buildings, impact of obstacles on evacuation flow, movement speeds, etc.). While this allowed describing outcomes broadly, it limits the depth of analysis for individual variables (e.g., meta-analyses on specific effects).

3.0 ANALYSIS OF THE LITERATURE

3.1 RESEARCH METHODS IDENTIFIED

The methodological distribution of studies in this review is shown in Figure 3. The analysis shows that experimental methods account for 39% and numerical methods for 30% of the studies reviewed, whereas statistical approaches comprise only 5% of the total. Experimental studies are primarily composed of evacuation drills (23%) and virtual reality (VR) experiments (21%), with experiments sub-category (30%) focusing on specific evacuation parameters such as movement speeds on stairs or door-opening times for mobility-impaired individuals. Despite the increasing trend of structured data use and machine learning in research, statistical studies remain a small portion of the available literature, suggesting a gap in leveraging predictive modeling techniques for evacuation studies. Notably, nearly a quarter of the experimental studies use VR simulations with human subjects. The sizeable share of VR-based studies indicates an emerging trend in the field of fire safety.

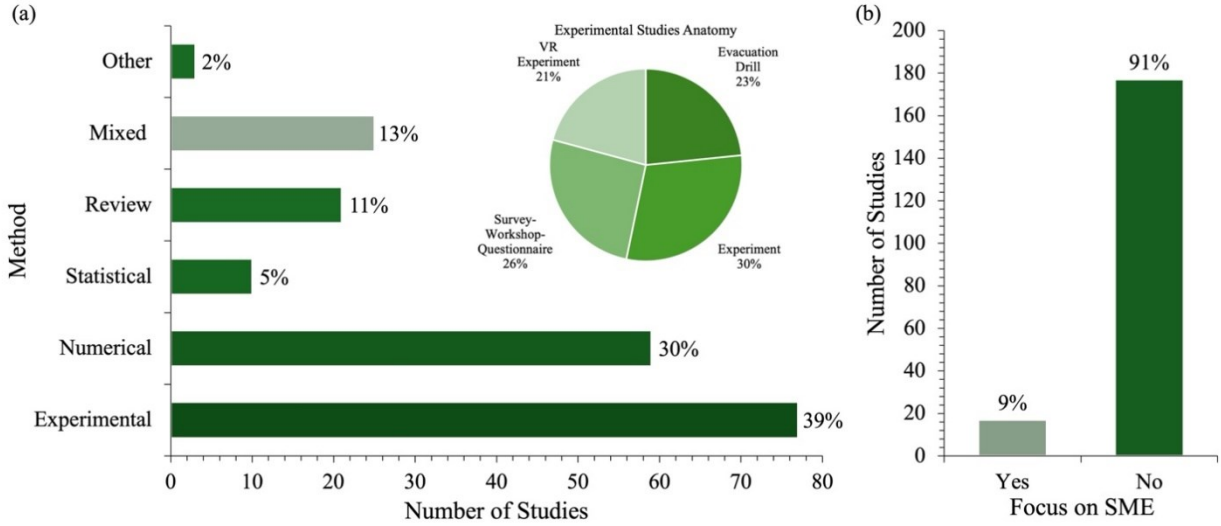

Figure 3: Chart showing (a) the proportional distribution of methodological approaches utilized in reviewed studies, including experimental (Evacuation Drills, Surveys, Experiments and VR), numerical, statistical, mixed-methods, and literature reviews (b) represent the percentage of studies which focused in whole or in part on a single mean of egress.

The majority of studies (91%) assessed buildings with multiple means of egress, which is attributed to the potential scarcity of current buildings with single stairways in North America where most studies originated (also see Figure 5). Broad insights are summarized in Table 4. Limitations included are either acknowledged by the authors of included studies or determined by the authors of this work.

Table 4: Strengths and limitations of studies reviewed

Method	Strengths	Main limitations	Sample studies
Laboratory experiments	• Allow studying specific factors in isolation. • Allow hypothesis testing and causal inference. • Offer high spatial and temporal accuracy in measuring evacuation-related variables. • Capture realistic aspects of human perception and behavior under controlled conditions.	• Artificial test conditions. • Homogeneous and non-representative participant demographics. Participants typically represent a narrow age range and health profile (e.g., young adults without medical or vision impairments). • Experimental settings can oversimplify real-life complexities by isolating individual factors, overlooking cumulative effects and interactions among multiple variables.	[54], [55], [56], [57]
Evacuation drills	• Offer sufficient spatial and temporal accuracy in measuring evacuation-related variables. • Capture aspects of human perception and behavior under naturalistic and safe conditions.	• Limited by participant demographics, frequently involving young, physically able participants with prior awareness that drills were occurring, thereby reducing ecological validity and the realism of occupant responses. • Lack of realistic scenarios associated with actual emergencies, such as reduced visibility, and real smoke inhalation, possibly resulting in non-representative outcomes. • Times and movement behaviours measured in drills can underestimate egress times during true emergencies. • Drills often involve predictable conditions, which may differ from conditions that may occur during real fire incidents, overlooking factors such as confusion, communication breakdowns, and the	[58], [59], [60]

		influence of ambiguous cues or instructions.	
Survey-based	• Allow rapid data collection across diverse population groups. • Facilitate analysis of demographic variations in evacuation-related perceptions and decision-making. • Enable participation from large sample sizes.	• Self-report data can be prone to biases such as recall inaccuracies, social desirability, subjective interpretations and potential media influence if the survey is conducted at a time near to a major incident. • The subjective nature of responses in predictive surveys, where reliance on stated preferences may occur.	[61], [62], [63], [64], [65], [66]
Virtual reality experiments	• Offer high spatial and temporal accuracy in measuring evacuation-related variables. • Enable safe and ethical testing of rare or high-risk conditions. • Support behavioral analysis within spatially similar and immersive building configurations. • Allows a high level of experimental control for the systematic manipulation of independent variables (e.g., exit signage, crowd density).	• Limited ecological validity[4]. Virtual simulations inherently simplify complex real-life environments, potentially failing to represent critical elements of fire scenarios, including heat, smoke, air movement, and physical fatigue, which could influence occupant behaviour. • Participant responses may not reliably reflect real-world actions due to awareness that scenarios are simulations. • Homogenous participant groups (such as undergraduate students) common in these studies limit insights into evacuation behaviours across varied demographic groups. • The technical constraints of VR platforms include limited sensory realism (e.g., lack of tactile, olfactory cues) and simplified interactions.	[67], [68], [69], [70], [71], [72]

[4] The effect of simulation graphical fidelity and its effect on results obtained from VR experiments is an undergoing research point

		• VR side-effects such as simulator sickness and lack of interface familiarity could impact participant interactions and responses. • Results acquired may require additional validation.	
Numerical simulations	Offer scalability, enabling simulations across a wide range of building sizes and scenarios allowing flexible manipulation of contextual variables such as building geometry, occupant load, and fire growth conditions. • Capable of modeling the interaction of multiple factors simultaneously.	• Simplified assumptions, such as uniform occupant movement speeds, standardized geometry, or predefined behaviours. • Current models neglect complex, spontaneous human behaviours during emergencies. • Limited experimental validation can weaken confidence in the results obtained.	[73], [74], [75], [76], [77], [78]
Statistical analysis of fire incident data	• Combine the inclusiveness of survey-based methods with the empirical grounding of experimental approaches. • Enable data-driven insights that support evidence-based fire safety strategies and predictive modeling.	• Insights dependent on the quality, completeness, and consistency of input data. • Often rely on secondary datasets, incident reports, and international statistics that may not fully reflect specific local conditions.	[79], [80], [81], [82]

3.2 TRENDS IN STUDIES

Figure 4(a) shows the chronological distribution for included studies which are divided based on the method of analysis. Figure 4(b) shows a histogram of the number of times each study was assigned to a particular category.

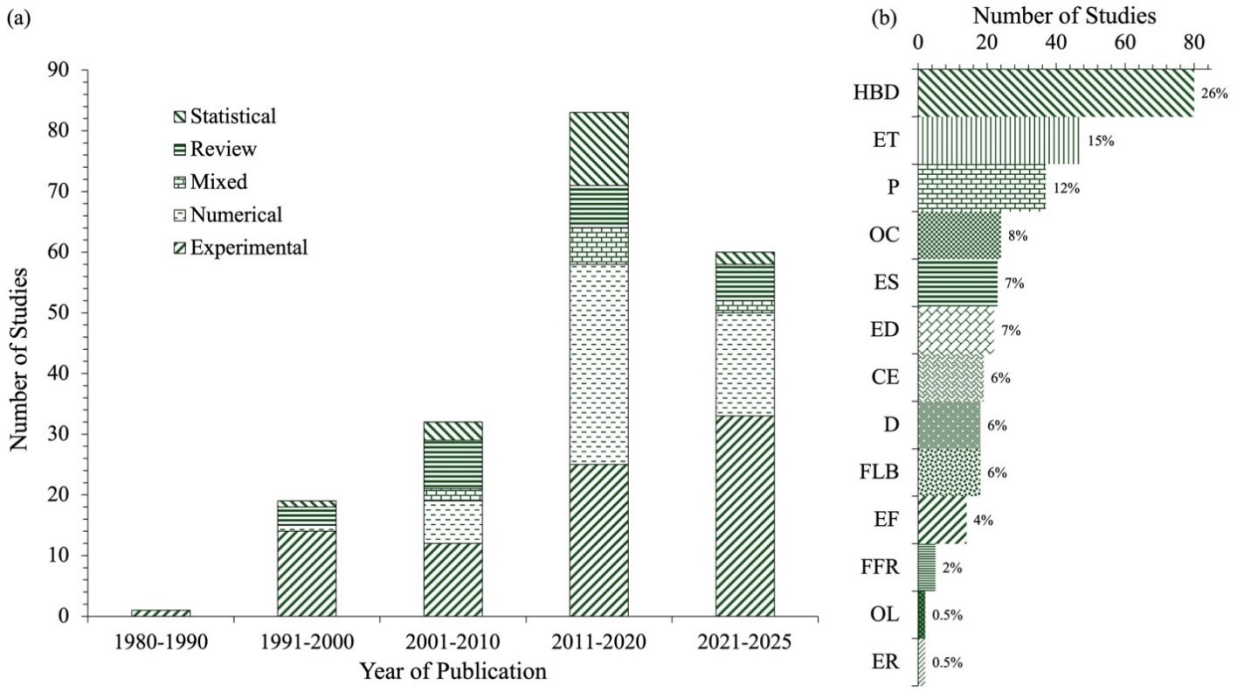

Figure 4:(a) Chronological distribution of reviewed studies by research methodology, spanning from 1980 to the present. Each bar represents the cumulative number of studies per decade. Note that the last bar only covers five years. (b) Histogram illustrating the total number of reviewed studies classified under each research category/theme. In cases where a study was assigned multiple categories, it was counted once for each relevant category. HBD: Human Behaviour and Decision making, ET: Evacuation Time, P: Protection of exit facilities, OC: Occupants Characteristics, ES: Evacuation Strategy, ED: Exit Design, CE: Communication during Evacuation, D: Demographics, FLB: Fire Load and fire Behaviour, EF: Evacuation Flow, FFR: Firefighting operations, OL: Occupants Loads, ER: Exit Redundancy.

Fire evacuation research has increased steadily since 2011, with earlier work (1980–2000) being sparse and primarily experimental. From 2001 to 2010, numerical and mixed-method studies gained traction. Between 2011 and 2020, numerical approaches grew to match experimental ones, while review-based and mixed methods also became more common. Statistical studies –which refers to studies that analyzed already available data from different sources – remain limited throughout, despite the potential of data-driven modeling to analyze complex multi-variable evacuation scenarios.

A key insight from Figure 4(b) is that studies categorized under ET are often also classified under HBD, since evacuation time is the primary metric used to quantify the impact of occupant behaviour and decision-making during fires. Also, the decreased number of studies for the protection of exit facilities category is attributed in part to the keywords and process used to obtain the final set of selected sources of evidence, similarly for the FLB category concerned with fire dynamics, which is the most widely researched discipline under fire safety engineering as a field. The small sample of studies under the

exit design category may suggest that particularly stair dimensions is a topic that require further focus. Additionally, its impact in the context of single-exit stair designs has yet to be explored, where diverse occupant groups with varying characteristics must share the same egress route.

Exit redundancy or the pros and cons of having multiple or single mean of escape is not on the radar of researchers despite possible benefits of single stairway (fewer fire safety measures, more space freed, etc.) and possible drawbacks of multiple stairways like occupants tendency to select familiar routes, which can result in uneven distribution and underutilization of available staircases or maintaining fire and smoke protection for multiple stairwells which will require additional resources.

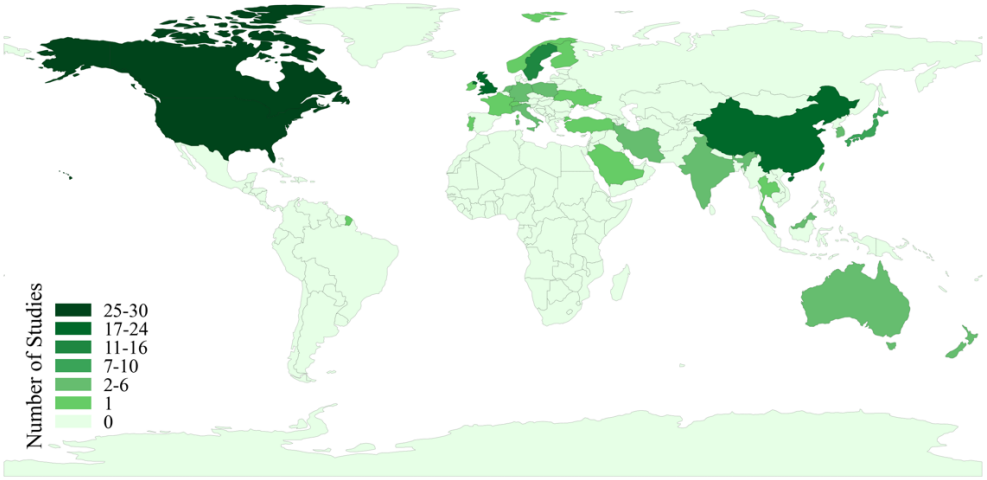

Figure 5: Choropleth map displaying the global distribution of studies included in this scoping review. The color gradient indicates the total number of studies originating from each country, with darker shades representing a larger number of studies.

Additionally, as evident in Figure 5, most research in this field originates in North America and Europe, meaning that the experimental data or statistical datasets informing numerical models if validated through data available in the literature are primarily derived from these regions.

3.3 ANALYSIS AND GAPS IN STUDIES

The results of this scoping review are organized into thematic categories reflecting factors influencing evacuation performance in residential buildings with focus on impact on single means of egress. Each subsection synthesizes findings from the studies included, highlighting methodological approaches, behavioural responses, design interventions, and contextual variables.

3.3.1 HUMAN BEHAVIOUR AND DECISION-MAKING

Human behaviour and decision-making include actions (e.g., preparatory actions, travel times), decisions (e.g., whether to evacuate or not, route choice) and experiences (e.g., perceived risk) of occupants during the evacuation process (pre-travel phase, travel phase). Understanding occupant behaviour is needed to quantify evacuation

performance (e.g., total evacuation time). As noted in section 3.1., human behaviour in fire was the most commonly studied factor influencing evacuation performance in buildings. Studies categorized under human behaviour and decision-making employed virtual reality (VR), surveys, or post-fire interviews to investigate evacuation-related factors in residential and educational settings. Numerical or experimental methods were used less frequently as a method of assessment in this category. Human behaviour studies identified in this study focused on the themes of pre-evacuation behaviour, decision-making, route choice, exit use, elevator use, modelling and theoretical integration. These are discussed further in the sections below.

3.3.1.1 Pre-evacuation behaviour, decision-making, and route choice

Multiple studies examined how occupants perceive risk, respond to alarms, and select evacuation routes. Lovreglio et al. [60] found that protective actions like alerting others and gathering belongings are common pre-evacuation behaviours, which current evacuation simulation models often exclude. Similarly, Zhao et al. [63] noted that half of 595 surveyed office occupants first alerted others before evacuating and that 80% took less than five minutes to begin evacuation, though those near the fire origin delayed evacuation attempting fire suppression. A study by Fahy [61], based on interviews with 435 evacuees from a high-rise office building fire, also identified delays due to pre-movement activities, which affected total evacuation times.

Glauberman [64] noted perceived risk to be low among residents on lower floors of high-rises without sprinklers due to proximity to ground-level escape options and noted a positive effect of building management involvement on preparedness. Noumeur et al. [59] found that prior fire drills among hotel staff – a demographic familiar with their building environment – reduced pre-evacuation time but raised generalizability concerns. Kinateder et al. [83] emphasized the need to quantify the impact of training on risk perception and preparedness, and the study identified a key limitation in varying interpretations of the term “risk perception.” Menzemer et al. [84] found a strong correlation between perceived preparedness and training quality, but quantitative assessment methods were lacking. Proulx et al. [85], based on interviews with evacuees from a real fire in a 36-storey building, revealed that most occupants selected the closest stairwell, though some later switched routes due to smoke, leading to fatalities in a single stairwell. Fu et al. [67], using VR, confirmed that high smoke levels deterred occupants from using risky routes. It also found that the behaviour of other evacuees significantly influenced occupants’ route choice, especially when smoke was present.

3.3.1.2 Factors affecting exit use

Zhang et al. [54] demonstrated that visibility impairment reduced stair descent speed, though group cohesion improved efficiency. Brown et al. [86], observed that ownership of firefighting tools reduced perceived risk, potentially delaying evacuation. Proulx [87] reported that inconsistent voice alarms during high-rise fires damaged trust and future compliance. Olander et al. [65] suggested dissuasive exit signage could redirect movement from unsafe routes, though adherence varied.

Averill et al. [88], based on the data collected from the 9/11 WTC evacuation accounts, identified delays caused by seeking information, congestion, and unclear instructions. While counterflow from emergency responders was commonly cited, it was not statistically linked to the reduced stairwell descent speed of evacuating occupants in this study. In the same direction, the study by Cłapa et al. [57] found that counterflow in stairwells had a negligible effect on the evacuation speeds of building occupants, whose average speed remained nearly unchanged regardless of firefighter presence. In contrast, the firefighters' average ascent speed decreased significantly from 1.02 m/s without counterflow to 0.51 m/s when the stairwell density was four persons/m², demonstrating the potential slowing effect of descending evacuees on firefighters during emergency response.

Route choice and familiarity were addressed in studies [55], [58] and [68]. Sagun et al. [55] showed occupants preferred familiar exits even when closer exits were available; however, this study did not correlate route choice to the presence of smoke. Benthorn et al. [58] confirmed this but noted that open doors with visible egress shifted preferences in their study. Teng et al. [68] found that both men and women avoided crowded exits.

3.3.1.3 Elevator use

Studies [85], [89], [90], [91], [92] focused on elevator use in evacuation contexts with a focus on human behaviour. Heyes et al. [92] found that floor height and waiting time influenced willingness to use elevators, while Gerges et al. [91] identified concerns like entrapment and smoke ingress. Kinateder et al. [89] noted that although elevators aid mobility-impaired occupants, behavioural data on their use remain limited in low- and mid-rise buildings. Mossberg et al. [90] found that participants preferred elevators during a VR high-rise evacuation, but design features like self-closing doors introduced anxiety. Min et al. [76] concluded that mixed stair and elevator evacuation plans improved efficiency in a 10-storey building, though elevator malfunctions and behavioural unpredictability were not modeled.

3.3.1.4 Modelling and theoretical integration

Several studies highlighted modelling limitations. Ronchi [93] reviewed evacuation models and identified missing sub-models for merging flows, elevators, and vertical egress. Hadjisophocleous et al. [75] introduced a fire risk assessment model, integrating fire dynamics, occupant behaviour, and economic factors, but noted a lack of empirical validation. Averill [94] outlined a general scarcity of experimental and computational data for emerging technologies like elevators.

Kuligowski [95] proposed adopting the Protective Action Decision Model (PADM) to better reflect how occupants assess risk and make evacuation decisions, emphasizing that occupant actions are determined by complex risk assessments rather than simple cues or personal characteristics alone. Lovreglio et al. [96] recommended building more representative behavioural datasets to bridge the gap between model assumptions and actual behaviours. We agree that integrating such data into simulations would improve predictive performance, especially for single-stair evacuations.

3.3.1.5 Summary of relevance to Single-exit designs and research gaps

- Only five (5) of the papers categorized as studying "human behaviour and decision-making" during evacuation specifically considered single-exit stair buildings and of the five, two investigated residential buildings. While the five (5) studies focused on single-exit stair buildings, no comparison was made to buildings with more than one exit stair relative to evacuation performance.
- Research concerning human behaviour and decision-making during egress does not often link its findings with the theme of protection of exit facilities (e.g., door opening or closing behaviour).
- There is a general scarcity of experimental and computational data for technologies like evacuation elevators for supplementing egress capacity particularly for buildings with single-exit stair configurations.
- Key findings for single-exit stair configurations include: studies showed that counterflow in stairwells has little impact on evacuation speed but can impede firefighter ingress, although studies on counterflow are few and further research on this topic is needed; occupants tend to prefer familiar or nearby exits; and the presence of smoke can discourage the use of certain exits.

3.3.2 DEMOGRAPHIC VARIABILITY AND FUNCTIONAL LIMITATIONS

This section summarizes studies that investigated the impact of functional limitations and demographic variation on evacuation performance. The reviewed work addresses occupant movement behaviours, design considerations for accessible egress routes, the role of elevators in evacuation, and interactions between diverse occupant groups in shared escape paths.

3.3.2.1 Dedicated evacuation routes and refuge areas

Studies [105], [106], [107] addressed the design and effectiveness of dedicated evacuation routes or spaces for occupants with disabilities. Qiao et al. [105] used simulations to demonstrate that dedicated exits could decrease evacuation times and improve the efficiency of vulnerable occupant evacuation, revealing a potential challenge in buildings with single exits. Similarly, Kuligowski et al. [106] indicated the need to evaluate the impact of dedicated evacuation devices, such as stair travel devices, which may cause congestion in single-exit stairwells. Relatedly, McConnell et al. [107] found through questionnaires and focus groups that occupant understanding of refuge areas remains limited.

3.3.2.2 Elevator use in evacuations

Elevator use during evacuations was the focus of studies [108], [109], [110], and [111]. Bukowski [108] noted that occupants have historically perceived elevators as unsafe in emergencies, emphasizing the need for intuitive signage, communication, and regular training drills. Supporting these points, Gerges et al. [109], using agent-based model [112] for simulations, demonstrated that optimized evacuation instructions could reduce evacuation time by approximately 50% but highlighted a key limitation: when elevators were available for occupants with functional limitations, occupants without disabilities could attempt to use them, leading to congestion and inefficiencies. This suggests a need for coordinated elevator evacuation strategies to balance efficiency and safety. Turhanlar

et al. [111] also concluded that lifts showed high reliability, which supports their use for evacuation. This study noted limited data available on the reliability of lifts. While elevators are often not available for evacuation, technological advancements in protecting and isolating elevator shafts suggest that elevators can be used for emergency evacuation, for occupants who cannot navigate stairs.

3.3.2.3 Shared routes and pedestrian dynamics

Studies [72] and [113] examined occupant behaviour in shared evacuation routes. Kuligowski et al. [113] measured stair evacuation speeds among older occupants with mobility limitations in assisted living buildings, noting that their movement speeds impact the evacuation performance of other occupants, representing an important point of research in single-exit configurations. Meanwhile, Smedberg et al. [72], through a virtual reality experiment, found occupants' exit choices were influenced by the decisions of others, notably wheelchair users.

3.3.2.4 Summary of relevance to Single-exit designs and research gaps

- Occupants with disabilities or mobility impairments have different movement speeds and space needs compared to occupants without disabilities. Design features like handrail placement, stair ergonomics, and door positioning can significantly impact their ability to evacuate safely.
- Some studies show that assistive devices (e.g., stair travel devices) can reduce evacuation time for vulnerable groups.
- Although traditionally seen as unsafe during fires, recent research shows that protected and well-managed elevators could be a reliable evacuation means of egress, especially for people who cannot use stairs. Clear communication and training are essential to prevent misuse by able-bodied occupants, which can cause delays.
- Mobility impairments, not commonly addressed in standard design assumptions, influence movement speed and gait stability, affecting both individual and group evacuation performance.
- In shared evacuation paths, people tend to follow the actions of others, which may reduce hesitation or confusion. However, slower-moving individuals can delay others, making occupant mix and interaction important considerations.

3.3.3 OCCUPANT CHARACTERISTICS

Studies included under this category highlighted the physiological and psychological factors affecting the movement and decision-making of evacuees. Agyemany et al. [122] reviewed the biomechanics of staircase descent, identifying fatigue and smoke as factors reducing evacuation speeds. Smoke impairs visibility and oxygen intake, exacerbating fatigue and slowing evacuees. Fujii et al. [123] experimentally tested walking speeds in smoky corridors and found that corridor illumination, rather than gender or emergency signage, had the most impact, nearly doubling walking speeds.

3.3.3.1 Summary of relevance to single-exit designs and research gaps

- Further analysis is required to determine the impact of smoke in corridors and stairwells in buildings with a single-exit stair, where congestion could be more pronounced, and subsequent evacuation delays more severe.

3.3.4 EXIT DESIGN

Exit Design studies addressed the influence of exit configurations and related factors on egress performance, often focusing on how features of the built environment and behavioral variables interact during evacuation. Within the Exit Design category, only one study in the reviewed sample investigated exit design as an independent variable affecting evacuation. Zheng et al. [119], using an extended Floor-Field model, analyzed how fire and smoke spread influenced evacuation dynamics. The authors found that when accounting for changing movement behavior due to fire conditions, two exits proved more efficient than a single exit of equivalent width. Studies indirectly related to exit configurations also provided relevant insights. El-Tawil et al. [78], in a numerical simulation of the Station Nightclub fire, examined the impact of social relationships on egress, finding that intimate social affiliations delayed evacuations, while unfamiliarity with the floor plan, unmarked and unclear alternative exits and the design of the main exit door limited safe exit choices.

3.3.4.1 Summary of relevance to single-exit designs and research gaps

- One relevant study suggested that when accounting for changing movement behaviour due to fire conditions, two exits were generally more efficient than a single exit of equivalent width. This highlights a potential limitation in single-exit stair designs where movement behaviour might be altered by smoke and fire proximity.

3.3.5 EVACUATION STRATEGIES

Studies in this category explored technological and modeling approaches to optimize egress planning. Siyao [120] examined the integration of Internet of Things (IoT) technology into fire evacuation planning for high-rise buildings (10-30 floors), concluding that real-time monitoring and decision-making capabilities reduced evacuation time. While IoT and other dynamic real-time instructions has the potential to improve dynamic evacuation strategies, its impact on single egress stair use requires further investigation, as real-time adaptation could either optimize limited egress routes or exacerbate confusion. Reneke et al. [121] developed an Egress Estimator Model, validated against International Maritime Organization (IMO) regulations and SFPE methodologies, to predict stairwell and elevator evacuation timing. However, the model assumes at least two exit stairs but incorporates other parameters, making it a tool for predicting the impact of a strategy and thus the need for future validation in single-exit stair configurations. Similar conclusions were drawn from studies focusing on the use of elevators for mobility-impaired occupants, suggesting that optimized mixed evacuation strategies may improve evacuation performance but require tailored research for buildings with only one stairwell.

3.3.5.1 Summary of relevance to single-exit designs and research gaps

- Technological solutions like IoT-based real-time evacuation guidance and predictive modeling show promise for improving evacuation efficiency, but their effectiveness and reliability, specifically in single-exit stairwell scenarios, remain uncertain. These systems may either enhance evacuation by optimizing limited routes or cause confusion, highlighting the need for targeted validation and research in single-exit configurations.

3.3.6 PROTECTION OF EXIT FACILITIES

Studies in the category of Protection of Exit Facilities predominantly examined the management of smoke spread and the effectiveness of passive and active fire safety measures in residential and high-rise buildings, with notable emphasis on stairwell protection, stairwell door impact, and occupant behaviour.

3.3.6.1 Smoke management in stairwells and corridors

A critical focus of the studies examined was the effectiveness of smoke management systems in stairways. Study [97], examining smoke control during the WTC attack, concluded that existing or hypothetical smoke management measures, including stair pressurization and HVAC dampers, would have been ineffective due to severe structural damage. The incident highlighted the vulnerability of single-exit scenarios, as two out of three stairwells in the south tower were destroyed, leaving a single stairwell (Stairwell A) operational above the impact zone. Although specific implications for mid-rise residential buildings are uncertain due to the uniqueness of the event (deliberate aircraft impact), the scenario demonstrated hazards associated with reliance on a single stairwell on one side and on the other hand a single stairwell functioned as a reliable escape method until structural failure. Hopkin et al. [80], employing Monte Carlo simulations (B-RISK model), assessed factors influencing corridor smoke clearance in UK residential buildings. The study identified occupant behavioural assumptions (particularly pre-evacuation delays) and fire-related parameters (fuel elevation, soot yield) as primarily influential, while sprinkler effectiveness had a lesser impact. Although simplified, the probabilistic methodology offers a practical approach for addressing problems involving multiple independent variables by assigning weights to evacuation parameters and quantifying associated risks.

In addition to the key factors discussed above, several less notable factors were identified. Studies [73] and [74] investigated the impact of door management on smoke spread and available safe egress time (ASET). McKeen et al. [73], using numerical simulations, found that continuously closed stairwell doors nearly doubled ASET compared to open-door scenarios. Notably, stair envelope tightness minimally affected smoke spread, pointing that door operation influences more smoke control outcomes. Conversely, Hopkin et al. [74] estimated door-opening times during evacuations via Monte Carlo simulations, showing variations from 10 to 19 seconds, dependent on apartment size. Accurate door swing times were identified as critical for precise evacuation modelling. Another factor that itself comprises multiple variables is facade combustibility and its impact on evacuation were studied experimentally by Taylor [98]. Testing various wall assembly

configurations, the study showed that fire spread intensified when combustible exterior materials (e.g., expanded polystyrene insulation, PVC siding, plywood) were coupled with air gaps. These conditions facilitated rapid flame propagation within wall cavities, particularly when fire entered from the exterior. Here, an example of two variables (façade flammability and door opening times) may affect the time available for egress despite being perceived as minor variables.

3.3.6.2 Summary of relevance to single-exit designs and research gaps

- The WTC case highlighted the critical risk of relying on a single stairwell for evacuation. While one stairwell remained usable for some time, the destruction of the others emphasized the danger of structural failure or blockage in single-exit configurations.
- Studies showed that smoke control systems (e.g., stair pressurization, HVAC dampers) may be ineffective in severe structural scenarios, reinforcing the need for robust design and redundancy in smoke management, especially in high-risk events.
- Simulations revealed that pre-evacuation delays and door management significantly impact evacuation outcomes. Closed stairwell doors can nearly double the available safe egress time (ASET), while accurate modeling of door-opening times is essential for realistic evacuation and ASET predictions.
- The use of combustible materials in exterior wall assemblies, especially when combined with air gaps, can accelerate fire spread and reduce egress time, as demonstrated in experimental studies and real-world incidents like the Grenfell Tower fire. Studies examining the impact of external fire spread on evacuation focused on high rise buildings.
- Impact on low- and mid-rise buildings and single-exit stair buildings has not been studied extensively.

3.3.7 Fire Load and Fire Behaviour

Studies categorized under Fire Load and Fire Behaviour (FLB) focused on characterizing fire dynamics in residential dwellings and the implications of fuel load distribution on fire spread and evacuation timelines. Bwalya et al. [118] conducted both small-scale and full-scale fire tests alongside numerical modeling using numerical simulations. Results demonstrated variation in fire load density by room type, with kitchens exhibiting the highest density (807 MJ/m²) and bedrooms contributing the largest overall fire load. The study emphasized that understanding fuel load distribution is critical, as compartmentation strategies should aim to position high fire load areas away from exit routes. In another work Bwalya et al. [77] reached a similar conclusion, thus reinforcing the importance of designing spaces with fire load density in mind to enhance overall fire safety. Bounagui et al. [99], analyzing fire incidents across three Canadian provinces (Ontario, Alberta, British Columbia), identified common ignition sources (cooking, heating, electrical faults, smoking materials) and noted reduced fatalities when functional smoke alarms were present. Alcohol consumption and delayed occupant response during nighttime fires increased fatality risks. Regional variations indicated notable numbers of heating-related fires in colder regions and cooking-related fires in Ontario.

3.3.7.1 Summary of relevance to single-exit designs and research gaps

- Understanding fuel load distribution in single-exit buildings is important, as compartmentation strategies should aim to position high fire load areas away from exit routes.

3.3.8 FIREFIGHTING OPERATIONS

Studies in this category examined the challenges and strategies faced by emergency responders during high-rise evacuations, with particular attention to operational procedures, evacuation tactics, and the use of building systems to support both occupant and firefighter safety. Studies representing less than two percent of the overall literature included in this review focused on firefighting operations; that in itself represents a clear limitation in fire safety research. The first study by Arewa et al. [66], conducted in the UK using focus groups with both firefighters (including international participants from UAE) and firsthand survivors, critically examined the "stay-put" strategy with the Grenfell Tower incident as a case study. It revealed that the stay-put strategy was not always followed as directed. However, its indirect addressing of single-exit stair configuration and the small sample size limit its broader applicability with other research suggesting opposite views [116]. Another study by Averill et al. [117], convened a multidisciplinary focus group to assess egress objectives in residential high-rise buildings in the USA. The study noted that risks for the fire service responding to a building fire tend to increase with building height and emphasized the role of emergency planning for both the responding fire department and building management. Kuligowski et al. [82] presented a review paper on high-rise administrative office buildings in the USA that explored how technological measures in elevators – such as water-tolerant elevator components, smoke protection, and real-time monitoring – can facilitate safe evacuation and expedite firefighter access by 15 to 30 minutes. The authors concluded that it is possible to achieve safe evacuation using elevators in parallel with the use of stairs. According to the authors, the key elements to successfully use elevators for evacuation are the operational and building management procedures, training and information on whether who should choose which means of evacuation and when. This is similar to the conclusion reached on the use of elevators for individuals with limitations, while suggesting that the use of elevators alongside stairs might offset some potential drawbacks of single-exit designs. In the aforementioned work, Cłapa et al. [57] found that the firefighters' average ascent speed decreased from 1.02 m/s without counterflow to 0.51 m/s when the stairwell density was four persons/m^2. In an experiment on firefighter counterflow in a six-storey building with two exit stairs, Peacock et al. [124] noted a small but measurable effect on movement speeds. Since this research was conducted in a multi-stair environment, further analysis is required to determine the full impact of firefighter counterflow in buildings with a single-exit stair, where congestion could be more pronounced, and subsequent evacuation delays more severe.

3.3.8.1 Summary of relevance to single-exit designs and research gaps

- Fire service-related studies make up less than 2% of the literature reviewed, representing a critical gap in understanding how emergency responders operate

in single-exit stair scenarios. This limits the development of strategies that balance occupant evacuation and firefighter access in such buildings.

- Research shows that firefighter movement speed in stairwells drops significantly under crowded conditions—from 1.02 m/s to 0.51 m/s at four persons/m²—highlighting how a single stairwell can become a bottleneck, especially during simultaneous evacuation and firefighting operations.
- Studies suggest that elevators, when equipped with protective technologies and supported by clear operational procedures, can be safely used alongside stairs to improve evacuation efficiency and firefighter access—even in single-exit configurations.

4.0 DISCUSSION

4.1 SYNOPSIS OF THE AVAILABLE LITERATURE

In this section, the findings are discussed in relation to the research questions posed in this review.

How is evacuation performance assessed in current building fire safety design?

Current building fire safety design assesses evacuation performance primarily through empirical and semi-empirical methods, as well as numerical simulations. Studies that used numerical methods opted for simpler geometries, which may indicate that to date, conducting full-scale, high-fidelity simulations might be challenging due to the multi-physics and the multi-scale nature of fire problems, limitations in computational resources or both. Moreover, the validation and scalability of numerical results remain an issue. Human factors, including occupant demographics such as age, gender, disability status, and cultural background, are often investigated individually rather than comprehensively, limiting the holistic understanding of evacuation performance. Virtual reality is an emerging trend with 21% of experimental studies within our sample relied on VR as a primary method. Data driven methods, despite being increasingly dominant in other scientific fields, were the least used without a single study within our sample employed artificial intelligence, machine learning algorithms, or optimization techniques such as genetic algorithms, ant colony, etc. or basic classification methods to quantify and predict evacuation time as an example variable based on other influencing parameters.

What are the implications of single-exit stair designs on evacuation performance?

Only nine percent of the reviewed studies explicitly focused on the impact of single-exit stair configurations, highlighting a significant gap in understanding the full implications of such designs on evacuation performance. Available research suggests potential risks due to limited egress options, but existing studies lack extensive parametric investigations involving multiple variables such as occupant load, human behavior, and fire dynamics.

Additionally, research shows that how doors are used during a fire can have an impact during evacuation. One study found that keeping stairwell doors closed almost doubled the time people had to get out safely, compared to when doors were left open. Another study showed that the time apartment doors remain open during evacuation varies—anywhere from 10 to 19 seconds depending on the size of the apartment—and this time has a direct impact on the quantity of smoke which could enter the common corridor and subsequently the tenability time in the corridor. Together, these studies suggest that simple factors like whether doors stay closed and how long they remain open can be just as important as building design features when it comes to protecting people during an

evacuation, and these factors require further study in the context of single-exit stair buildings.

What research gaps exist concerning fire safety of single-exit stair designs or how evacuation performance is being evaluated?

The following research gaps emerged from this review:

- Lack of studies on evaluating the implications of single-exit stair configurations explicitly: Only nine percent of studies address the question of single vs. dual exit stair configuration and none explicitly. In particular, the following topics are not at all or only partially addressed: impact of occupant loads and obstacles, evacuation flow, and evacuation time. In addition, communication during evacuation was often paired with the human behaviour and decision-making category, but not as the main objective for enhancement.
- Minimal representation of firefighter perspectives, with only two percent of studies considering their influence on evacuation outcomes.
- Lack of studies on the effectiveness and limitations of virtual reality (VR) simulations compared to real-life fire drills.
- Absence of advanced data-driven techniques such as artificial intelligence, machine learning algorithms, and optimization methods.
- Insufficient large-scale parametric studies examining multiple interacting variables.
- Inadequate examination of how occupant demographics collectively affect evacuation, often focusing narrowly on single demographic, with cultural and socio-economic variations requiring deeper focus.
- Lack of quantified studies on the impact of prior training or existing knowledge on evacuation outcomes.
- Narrow research focuses on mobility impairments, neglecting other physical and cognitive functional limitations, especially within diverse multicultural residential contexts.
- Predominant use of homogeneous and non-representative participant groups (typically early adulthood) in evacuation drills, reducing the representativeness of real-world scenarios.

4.2 FUTURE RESEARCH

In addition, the following gaps or future research directions identified related to themes discussed:

- Lack of studies on post evacuation behaviour of occupants and the effect of potential re-entry including re-entry behaviours, temporary refuge usage, and risks of re-entering during an ongoing incident, which are particularly relevant when only a single stairwell is available.

- Demographic barriers beyond physical limitations including impact of language barriers affecting ability to comprehend written or auditory emergency instructions.
- Lack of studies on the risk of reduced technological access in an era characterized by a reliance on technology in fire safety measures. For example, limited access to smartphones or the Internet during an emergency could restrict the effectiveness of digital alerts or real-time evacuation guidance.
- The impact of non-static occupancy and dynamic population loads is underrepresented. Occupancy fluctuations (e.g., short-term rentals, family vs. single occupants, shift work) and patterns of apartment use may affect evacuation flows due to difference in perception towards the dwelling.
- Comparison between evacuation time in single vs multiple stairways buildings under the same conditions.
- Impact of obstacles on evacuation flow in a single-stair configuration.
- Comparison from an economic perspective on single vs multiple means of egress configurations.
- The reviewed studies did not examine variables such as gender differences, prior education or training, or socioeconomic status.

5.0 CONCLUSION

This scoping review summarized current knowledge and identified research gaps regarding evacuation performance in residential buildings, focusing specifically on single-exit stair designs. Key findings indicate limited research explicitly addressing single-exit stair scenarios, demographic diversity in study populations, and adequate incorporation of realistic human behaviour into evacuation models. Future studies should emphasize diversified methodologies, inclusive participant demographics, and robust statistical analyses to improve evacuation modeling accuracy. Addressing these identified gaps will contribute to more reliable risk quantification, facilitating informed decisions in building safety design and enhancing occupant evacuation outcomes.

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