

A Systematic Review of Digital Technologies for Emergency Preparedness in Buildings

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Abstract

Natural and human-made hazards are increasing due to global warming and human activities. Occupant evacuation in complex buildings remains challenging due to unfamiliar building layouts, communication failures, and unpredictable occupant behavior. Therefore, this study aims to explore how integrating digital technologies enhances emergency preparedness, supports occupant decision-making during evacuation, and improves occupants' situational awareness. We conducted a PRISMA-guided systematic literature review across Scopus, IEEE Xplore, and ProQuest Discover, analyzing 31 high-quality journal articles relevant to the research. The focus was on integrating digital technologies to support occupant situational awareness and evacuation outcomes. This review explores the integration of Internet of Things (IoT), Building Information Modeling (BIM), Virtual Reality (VR) / Augmented Reality (AR), Artificial Intelligence (AI), and Digital Twins (DTs) for emergency preparedness, supporting real-world applications. This review highlights three research questions: (1) Evaluate how current digital technologies affect occupant emergency preparedness in buildings; (2) Identify the challenges that limit the effectiveness of digital technologies across key emergency preparedness stages; (3) Understand how digital technologies can support occupant emergency preparedness. The review compiles evidence and presents a conceptual framework to support the integration of digital technologies into occupant-focused emergency preparedness, providing practical guidance for the future direction of risk management research.

Keywords: digital technologies; emergency preparedness; buildings; evacuation; situational awareness



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1. Background

In recent years, there has been a notable rise in natural hazards such as wildfires, earthquakes, floods, and hurricanes, attributed to global warming [1–3]. Additionally, human-made hazards such as pandemics, crowd congestion, and terrorist attacks have become more common due to economic development [1–3]. Although studies often focus on structural damage [4] and construction weaknesses [5,6], research on building occupants to understand their behavior and decision-making processes during evacuations in disasters is equally essential for advancing effective emergency preparedness and may pose significant risks during emergencies [7–9].

This study employs a PRISMA-guided systematic literature review to investigate the digital technologies integration to enhance emergency preparedness, occupant situational

awareness, and decision-making in buildings. For example, some casualties result from unclear evacuation routes, insufficient time, and limited emergency knowledge [10,11]. Notably, emergency preparedness within buildings is a vital component of risk management, aimed at minimizing risks and improving occupant safety during multi-hazard events [12]. It is crucial to have clear evacuation instructions to lower the risk of casualties and injuries. However, traditional emergency preparedness faces many challenges during crises, including complex building layouts, confusing instructions, and limited evacuation knowledge [4,13,14]. In traditional evacuation situations, occupants primarily rely on signage and pre-made plans rather than real-time alerts [15]. These issues highlight the need for innovative strategies to enhance emergency preparedness procedures and improve safety outcomes.

We identify several key research gaps that could significantly impact emergency preparedness. Firstly, although relevant research on multi-hazard preparedness exists, most studies focus on single threats, usually fire [10,11,16,17], and cascading events are relatively rare. Secondly, most research emphasizes simulation in virtual environments, with few examples of digital evacuation tools used in real buildings [11,18,19]. Thirdly, Lovreglio and Kinateder [20] note that VR and drill-based training often fail to accurately replicate actual occupant behavior. Fourthly, Abdusalomov et al. [21] stress the importance of sensor accuracy and field validation for IoT-based systems. As digital technologies rapidly evolve, they may be replaced by newer versions. The potential of combining advanced digital technologies remains underutilized. Finally, current emergency preparedness still depends on both human and digital interventions. Very few studies provide quantitative outcome measures or occupant feedback [11]. Only a few mention evacuation times, including ASET (Available Safe Egress Time) and RSET (Required Safe Egress Time). For example, Abdullahi et al. [16] demonstrate ASET/RSET as performance indicators, while Saini et al. [22] demonstrate reductions in total evacuation time through the IoT integration. However, field trials, occupant surveys, and live system performance data are rarely collected, which hinders a thorough assessment of system effectiveness. The review highlights research gaps and helps develop an adaptive framework to enhance research on how digital technologies are integrated to improve emergency preparedness, occupant situational awareness, and evacuation decision-making in buildings. This paper is structured as follows: an introduction to emergency preparedness, digital trends, and the interaction between digital technologies and emergency preparedness in Section 2; an explanation of the methodology in Section 3; the results for the proposed architecture layers for digital technologies integration in Section 4; and a proposed framework of discussion in Section 5. The conclusion on digital technologies for emergency preparedness in buildings is in Section 6.

2. Introduction

Recently, the frequency and intensity of natural hazards (e.g., wildfires, earthquakes, floods, and hurricanes) and man-made hazards (e.g., pandemics, crowd incidents, and terrorist attacks) have increased [23]. In the United States, fire fatalities in residential buildings often result from issues with exits and escape routes [17]. Relevant research emphasis centered on occupants is equally essential because occupants may encounter various challenges, including personal factors (e.g., fear, slow movement, and rescuing others) and environmental factors (e.g., limited visibility, blocked exits, and high temperatures), which create additional dangers and influence evacuation outcomes [17,24]. These factors expose vulnerabilities in both building structures and occupant safety, as well as in social systems.

2.1. Emergency Preparedness

Emergency preparedness ensures that occupants can evacuate safely or take appropriate actions during an emergency by relying on clear evacuation routes, functional communication policies, and occupant situational awareness of emergency procedures [25–28]. However, current emergency preparedness in buildings faces significant challenges. Human behavior factors (e.g., lack of knowledge and unclear instructions) during emergencies are often unpredictable, posing a risk of injury [28]. Additionally, hazards and uncertainties, such as rapid fire spread and structural damage from earthquakes, complicate evacuation efforts [29]. Therefore, there is a need to develop practical guidelines to improve occupant situational awareness, knowledge base, and decision-making for emergency preparedness in buildings.

2.2. Digital Trends

Digital technologies offer practical solutions to overcome the limitations of traditional preparedness by improving occupant situational awareness, training, decision-making, and enabling dynamic navigation [7,20,30,31]. This review classifies the literature into field deployments, simulation studies, and conceptual work to evaluate the maturity and relevance of digital interventions. Virtual Reality (VR)/Augmented Reality (AR) technologies boost immersive training, navigation, and familiarization with building layouts [16]. Additionally, Artificial Intelligence (AI) supports data analysis, emergency prediction, and danger classification [13,32]. Building Information Modeling (BIM) integrated with the Internet of Things (IoT) enables visualization of building layouts using wireless sensor networks (WSNs) and Long-Range Radio (LoRa) technology, thereby improving internet connectivity during emergencies [16]. Notably, Digital Twins (DTs) add new layers to enhance occupant safety in emergency preparedness applications [16,18,33].

2.3. Interaction of Digital Technologies and Emergency Preparedness

Prior work clusters into three complementary streams: (1) sensing & localization (IoT, sensors, Bluetooth Low Energy (BLE), LoRa, and Radio frequency identification (RFID)) for real-time hazard detection and occupant localization [13,18]; (2) modeling and decision support (BIM, AI, DTs, and Fire Dynamic Simulation (FDS)) for hazard prediction and route optimization [17,26]; and (3) training and human factors (VR/AR, dashboards, and serious games) for occupant situational awareness and rehearsal [8,15,23]. The Appendix A (Table A1) summarizes the evidence supporting these streams. This integration clarifies how digital technologies integration (sensing, modelling, and visualization) combine to address emergency preparedness stages (detection, communication, training, navigation, and evacuation) and sets up the research questions that guide our analysis (see Section 3.1). This integrative perspective provides the conceptual foundation for the research questions addressed in the following sections.

3. Methodology

3.1. Review Design

This study adopts a systematic literature review (SLR) following the PRISMA 2020 guidelines to examine the application of digital technologies in emergency preparedness for buildings, with an emphasis on occupant safety. The review, in accordance with the PRISMA flow diagram, illustrates the study identification, screening, eligibility, and inclusion procedures [34]. These four stages of article screening are shown in the PRISMA Flow Diagram (see Figure 1). Data screening, analysis, and coding in NVivo 13, VOS viewer 1.6.20, and Microsoft Excel 16.102.2. Furthermore, VOS viewer was used exclusively

for bibliometric and keyword co-occurrence analysis, while NVivo supported in-depth qualitative coding and thematic synthesis of articles.

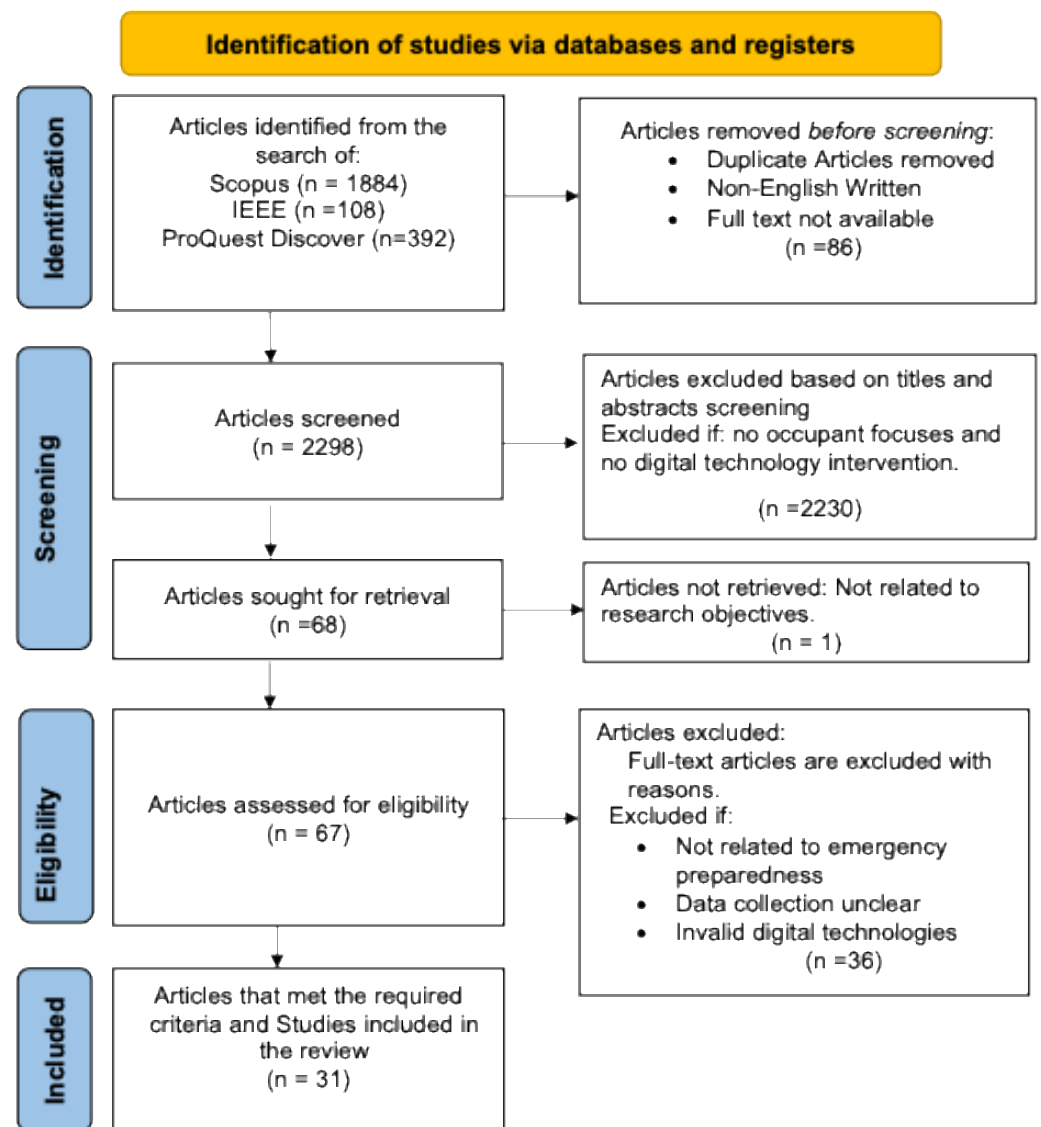


Figure 1. PRISMA Flow Diagram.

3.2. Search Strategy

A comprehensive literature search was conducted across three bibliographic databases: Scopus, IEEE Xplore, and ProQuest Discover. A search was conducted on 15 July 2025, covering publications from 2015 to 2025, to verify the relevance of digital technologies. The search strategy combined vocabulary and terms describing (1) digital technologies, (2) emergency preparedness or evacuation, (3) building contexts, and (4) occupants and people. As shown in Table 1, the keyword search strings are used across three databases. These keyword strings were used to identify relevant articles on digital technologies for emergency preparedness in buildings, with a focus on occupant safety. The retrieved records were screened against the exclusion criteria outlined in the following sections.

Table 1. List of Search Strings.

Search Database	Search String
Scopus IEEE	“digital technolog*” OR “smart technolog*” OR “advanced technolog*” OR technolog* OR “emerging technolog*” OR “State-of-the-art technolog*” OR “Innovative technolog*” OR “breakthrough technolog*” OR “Cutting-edge technolog*” OR “Digital innovation” AND
ProQuest Discover	safe* OR evacuat* OR prepared* AND building* OR “indoor” OR school* OR hospital* OR hous* AND occupan* OR user* OR people

The article selection process involved four main stages: Identification, Screening, Eligibility, and Inclusion. The initial database search yielded 2384 articles. After applying the inclusion and exclusion criteria listed in Table 2 and conducting full-text screening, articles were excluded if they did not focus on occupants, lacked a transparent methodology for general emergency analysis without a decision-making evacuation focus, or used invalid technologies. Ultimately, 31 high-quality articles were selected for the final review. The PRISMA flow diagram, which details the selection of relevant articles (see Figure 1). These articles were selected using the systematic literature review search strategy.

Table 2. Inclusive and Exclusive Criteria.

Steps	Inclusion Criteria	Exclusion Criteria
Identification	All records from three databases were retrieved, duplicates removed.	Duplicate removal in this phase. Non-English written.
Screening	Titles and abstracts discuss digital technologies for occupant safety for emergency preparedness in buildings.	Duplicates ($n = 86$) removed. No occupant focus (e.g., structural analysis only). No digital technologies intervention.
Eligibility	Full texts demonstrating implementation. Clear method and results. Valid digital technologies intervention in the emergency preparedness stages.	Not related to the emergency preparedness stages. Unclear data collection method and results Technologies used are invalid or unrelated.
Inclusion	Empirical studies of digital solutions evaluating effectiveness and occupant safety for emergency preparedness in buildings.	Studies not meeting all above criteria upon final review.

3.3. Research Questions

The research question aims to understand how digital technologies are integrated to improve emergency preparedness, occupant situational awareness, and evacuation decision-making in buildings. The following research questions (RQ1 to RQ3) explore how current digital technologies can be integrated into emergency preparedness and into enhancing occupant situational awareness to achieve more efficient and safer technological application scenarios (see Appendix A).

RQ1: How do current digital technologies affect occupant emergency preparedness in buildings?

RQ2: What are the challenges that limit the effectiveness of digital technologies across key emergency preparedness stages (detection, communication, training, navigation, and evacuation)?

RQ3: How can we integrate technologies to support occupants' emergency preparedness?

To address RQ1, a structured search strategy was used to identify studies examining the application of digital technologies, such as BIM, IoT, AI, VR/AR, and DTs, in emergency preparedness contexts. A qualitative thematic analysis was then conducted to synthesize how these technologies support occupant awareness, decision-making, and behavioral responses during emergencies. This analysis provides a systematic understanding of the functional roles of individual technologies across different preparedness stages.

With respect to RQ2, the review focuses on identifying recurring technical, organizational, and operational challenges reported in existing studies. These include data latency, interoperability, system reliability, privacy, and occupant–technology interaction, which may limit the effectiveness of digital technologies integration solutions across emergency preparedness stages.

Finally, RQ3 builds on the findings of RQ1 and RQ2 by examining how individual digital technologies are combined into proposed integrated frameworks. By synthesizing evidence on sensing, modelling, and visualization functions (see Appendix A), the review explores integration strategies that support more coordinated and efficient emergency preparedness.

3.4. Analysis Approach

To systematically analyze the selected studies, a qualitative content analysis was used. After identifying 31 relevant articles through a PRISMA-guided selection process, a qualitative analysis was conducted. All 31 papers were imported into NVIVO 13 and Excel for coding and qualitative analysis. The analysis involved three main steps: (1) Data preparation involved uploading each article based on key dimensions aligned with research questions: (a) digital technology types, (b) emergency stage (detection, communication, training, navigation, evacuation), (c) occupant-related outcomes, and (e.g., evacuation time and ASET/RSET values). (2) Keyword frequency analysis: Text query and matrix coding identified high-frequency terms and co-occurrence patterns. (3) The coded data were organized into themes highlighting trends: human behavior and vulnerable occupants, training and simulations, digital technologies integration, and challenges across emergency preparedness stages. By combining systematic coding with keyword analysis, the review synthesizes findings and provides empirical insights into the significance of technology and research focus in real-world validation. This evidence supports the review's research questions (RQ1–RQ3), which examine the topics studied, the evidence-collection methods, the technology's functions, the remaining challenges, and potential solutions. Additionally, to enhance analytical reliability, the primary author consistently applied a structured coding framework across all included studies. The coding process followed a clearly defined analytical scheme aligned with the research questions, ensuring consistency across the qualitative synthesis.

3.5. Inclusion and Exclusion Criteria

Inclusion criteria:

- Population setting: studies in building contexts (schools, hospitals, offices, and residential buildings) that address occupant emergency preparedness or evacuation.
- Intervention technology: digital interventions (BIM, IoT, AI/ML, VR/AR, and DTs) applied to preparedness, training, navigation, communication, or evacuation decision support.

- Study type: empirical field deployments, simulation experiments that report occupant outcomes or technical performance *in* journal articles.
 - Language and period: English, published 2015–2025.
- Exclusion criteria:
- Purely technical studies without occupant focus (e.g., structural analysis only).
 - Conceptual papers, reports and book chapters.
 - No clear methodology or application of digital technology.

3.6. Data Extraction

Data extraction was conducted through a structured, iterative process designed to support both bibliometric analysis and qualitative thematic synthesis. Two complementary tools, VOS viewer and NVivo, were used, each serving a distinct analytical purpose.

First, bibliographic data (including authors, publication year, and citation information) were exported from the selected databases and used as input for Vosviewer. This tool was used to explore relationships among the reviewed studies, including keyword co-occurrence patterns, thematic clustering, and structural connections between research topics. The bibliometric analysis provided a macroscopic overview of the literature's intellectual structure and informed the identification of dominant research themes and emerging trends. Importantly, the VOS viewer was used solely to analyze document relationships and did not replace in-depth content analysis.

Second, full-text articles of all included studies were imported into NVivo to support qualitative data extraction and thematic analysis. NVivo was primarily used to organize and code themes, keywords, and conceptual categories derived from close reading of the articles.

Finally, data were extracted using a structured Excel form. Fields included: (1) citation (authors, year, and source); (2) country; (3) study design (field deployment, simulation, or conceptual); (4) digital technology types studied (IoT, BIM, AI, VR/AR, and DTs); (5) emergency preparedness stage(s) addressed (detection, communication, training, navigation, and evacuation); (6) participant characteristic and demographics; (7) outcome measures reported (evacuation time, navigation accuracy, ASET/RSET, localization error, and situational awareness measures); (8) main findings; (9) notes on integration with other technologies. To enhance reliability, the extracted data were reviewed and refined through repeated reading and cross-checking of the source articles. The final dataset, comprising coded themes, keyword classifications, and study attributes, served as the empirical basis for subsequent synthesis. Additional methodological details and supporting data are provided in the Supplementary Materials (see Table S1).

4. Results

4.1. Selected Publication Trends

The co-authorship and 31 selected articles meeting the inclusion criteria were published between 2015 and 2025 (see Figures 2 and 3). The number of publications increases after 2021, indicating a rise in the use and upskilling of immersive simulation tools (VR/AR) and in affordable sensing hardware (IoT) [35], as well as in research interest, driven by the rising demand for remote training during and after the COVID-19 pandemic. Overall, Figure 3 indicates a steady increase in publications after 2021, reflecting growing research interest in digital technologies for emergency preparedness. To further understand thematic evolution, keyword-based analysis is presented in Section 4.2.

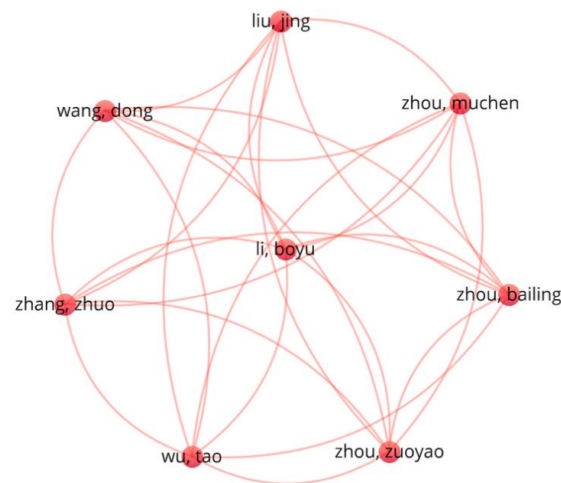


Figure 2. Publication Co-Authorship.

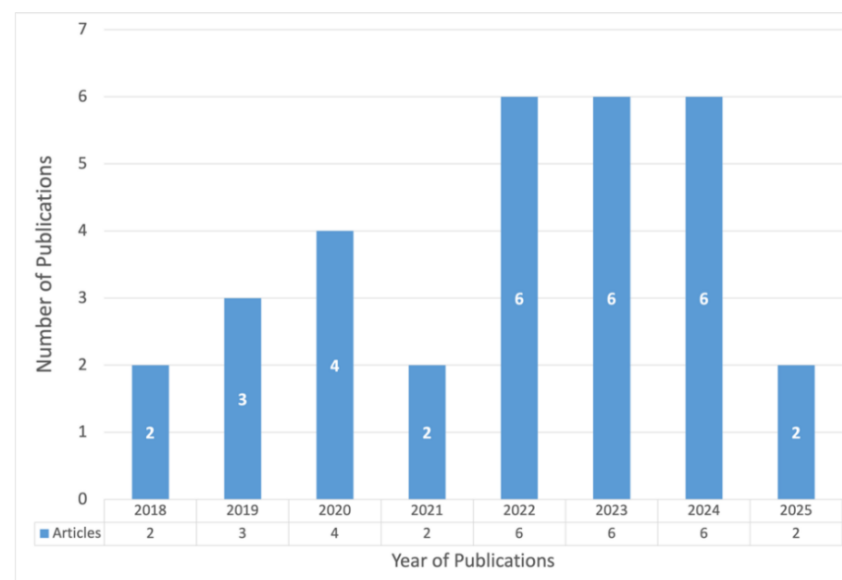


Figure 3. Annual Publication Trends of Selected Studies.

4.2. Keyword and Co-Occurrence Network

The node depicts the keyword co-occurrence network using VOS viewer, revealing distinct yet interconnected clusters (see Figure 4). This implies that node size indicates term frequency across the 31 articles. Line thickness represents co-occurrence strength. The network shows two main clusters: a sensing–modelling cluster (IoT, BIM, and AI/ML) and an immersive/training cluster (VR/AR, training, and participants). Cross-cluster links (e.g., ‘evacuation’, ‘navigation’) indicate terms frequently discussed in integration studies. Terms related to hazards and responses (“earthquakes,” “fire emergencies,” “Evacuation,” “navigation”) connect these axes. Node size reflects the frequency with which each term appears, and link strength indicates the level of co-occurrence. This pattern from Figure 5 suggests that recent research increasingly emphasizes integrated, multiple digital technologies solutions rather than isolated digital technologies. Additionally, when imported into NVivo 13, the data display keyword frequency, including terms such as “evacuation,” “building,” “IoT,” “training,” and “time,” with a focus on evacuation-related topics (see Figure 5). The top 5 terms are presented with counts, e.g., “evacuation ($n = 10$), IoT ($n = 3$), BIM ($n = 3$), training ($n = 8$), time ($n = 4$). These visualizations collectively represent the research scope, with an emphasis on emergency evacuation technologies and strategies.

with other multi-hazards receiving comparatively limited attention. The prevalence of fire incidents remains steady across various national settings, as shown in Table 3, and fires often cause serious effects, including reduced visibility, respiratory problems, and eye irritation from smoke [14], highlighting the importance of prioritizing prevention, preparedness, and response strategies within emergency management frameworks.

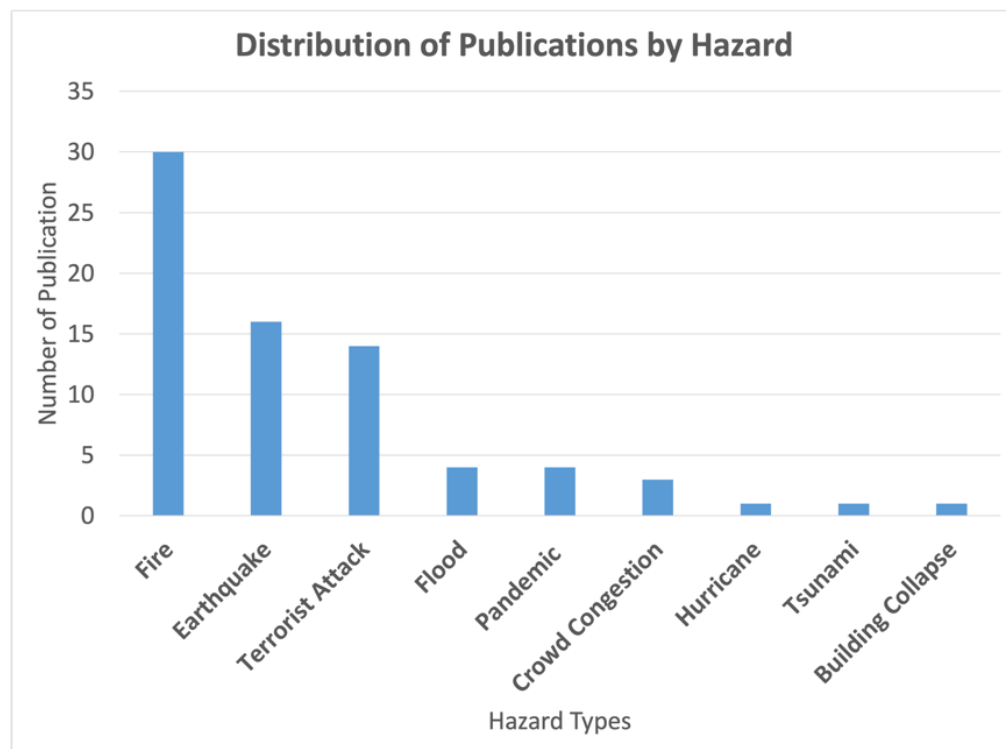


Figure 6. Distribution of Publications by Hazards.

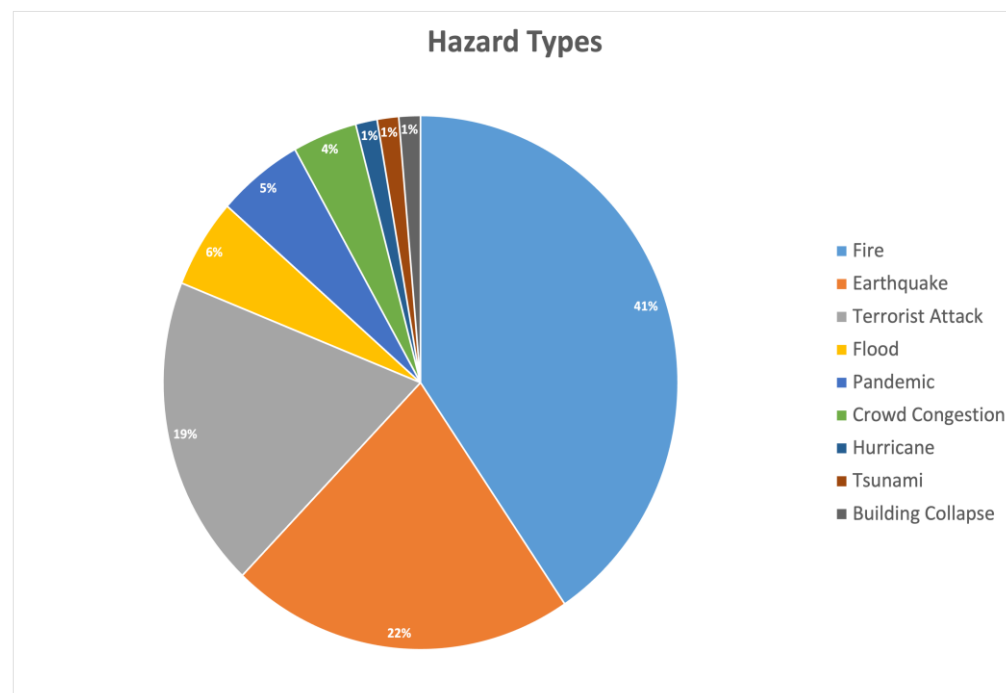


Figure 7. Percentage of Hazard Types.

Table 3. Frequency of Emergency Types by Country.

No.	Country	Frequency of Articles	Emergency Types
1	New Zealand	3	Fire, Earthquake, Tsunami, Radioactive Accidents, Counterterrorism
2	Australia	1	Fire
3	USA	3	Fire, Earthquake, and Shooter event
4	France	1	Fire
5	Canada	1	Earthquake, Flood, Fire
6	India	3	Fire, Pandemic Constraints, Potential Hazards, Earthquake, Building Collapse, Gas Leaks, Explosion
7	Saudi Arabia	1	Fire, Crowd congestion, Transmission risks of COVID-19
8	Korea	3	Fire
9	China	5	Fire, Illegal invasion, Overcrowding
10	Turkey	2	Fire, Terrorist Attacks, Chemical Attack, Earthquake
11	Iran	1	Fire, Earthquake, Inundation, Hurricane
12	Saudi Arabia	1	Earthquake, Fire, Flood, Terrorist Attack
13	Portugal	1	Fire
14	Italy	1	Fire, Pandemic, Flood, Earthquake
15	Malaysia	1	Fire
16	Democratic Republic of the Congo	1	Fire
17	Chile	1	Fire, Earthquake

4.4. Frequency of Digital Technology Use

This section addresses Research Question 1 to identify how current digital technologies impact emergency preparedness and occupant behavior in buildings, focusing on occupant situational awareness, decision-making, and evacuation. As shown in Figure 8 and Table 4, BIM is the most frequently reported technology ($n = 18$), valued for its ability to integrate data and facilitate visualization and evacuation [17]. Followed closely by IoT ($n = 17$), which enables real-time monitoring, hazard detection, and communication through various sensors and cameras [23], and AI ($n = 16$), which facilitates adaptive decision-making under changing conditions [13]. In addition, VR ($n = 13$) features prominently, with immersive training, realistic emergency scenarios, and enhanced safety awareness to help occupants build confidence [20], and AR ($n = 11$) assists with navigation and location awareness during emergencies, combined with portable devices such as smartphones [16]. While Digital Twins are less common ($n = 6$), they provide advanced simulation capabilities for complex scenarios [36]. This distribution reflects a research focus on well-established, data-rich platforms alongside increasing interest in immersive and simulation-based tools.

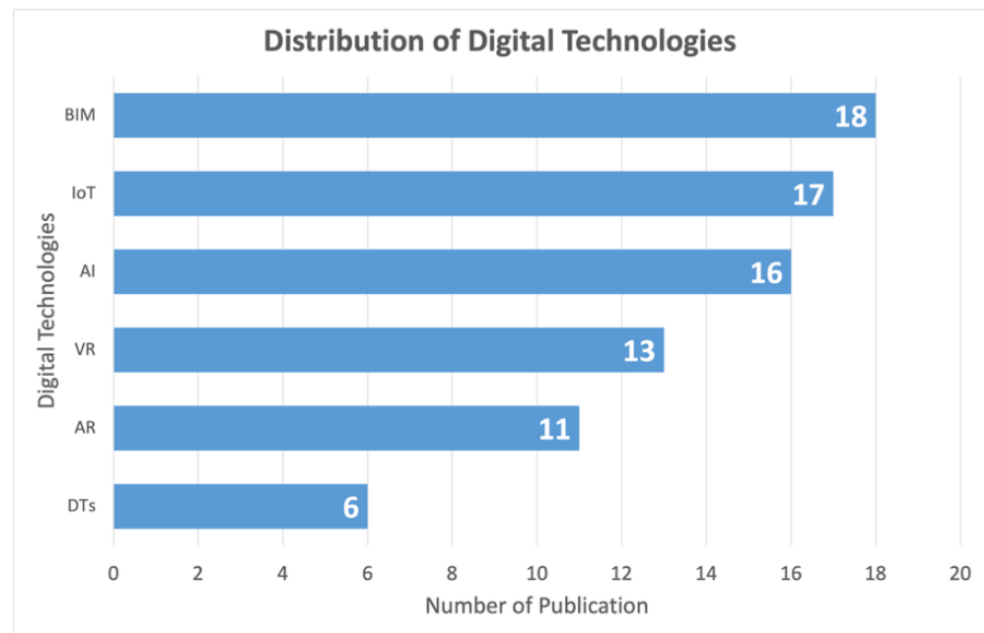


Figure 8. Distribution of Digital Technologies Publication.

Table 4. Digital Technologies Publication Frequency.

No.	Digital Technology	Frequency
1	Building Information Modeling (BIM)	18
2	Internet of Things (IoT)	17
3	Artificial Intelligence (AI)	16
4	VR	13
5	AR	11
6	Digital Twins (DTs)	6

4.5. Challenges in the Effectiveness of Digital Technologies Across Emergency Preparedness Stages

This section addresses Research Question 2 by analyzing the challenges that limit the effectiveness of digital technologies across key emergency preparedness stages (e.g., detection, communication, training, navigation, and evacuation). Firstly, complex buildings cannot often update information in real time [23], even when network connectivity is available during emergencies [37]. Hazards in building environments are unpredictable, including blocked exits, long travel distances, elevated carbon monoxide levels, and temperature variations [4,29]. Another factor relates to human behavior, such as fear, visibility, and congestion [27,28]. Secondly, BIM and AR integration may introduce processing delays during live events [35]. Relying on a single technology is unlikely to yield the best results in disaster situations. The effectiveness of integrating these technologies remains a central challenge [10].

Thirdly, advanced technologies such as BIM, AR, IoT, and DTs are often constrained by insufficient occupant training and limited user knowledge [23]. Fourthly, trust deficits persist in data privacy and security [13,23,26]. At the same time, another significant challenge to their practical implementation stems from computational limitations, such as data storage capacity and data processing speed [11]. Fifthly, several authors emphasize that improving sensor accuracy and conducting field validation are crucial, as lab performance often degrades in real-world conditions due to occlusions, environmental noise, and communication latency [7,13,18,21]. Finally, the effectiveness of a specific technology in

one hazard scenario (e.g., illegal invasion, overcrowding, or fire) [36] does not guarantee its suitability for other hazard types, such as floods and earthquakes [19]. Ongoing real-world conditions and scenario-based experiments are essential for collecting more precise performance data and enhancing the flexibility and effectiveness of these technologies in different emergencies.

4.6. Human Behavior for Training and Vulnerable Occupants

This section addresses Research Question 3 to investigate how integrating technologies can help occupants, including vulnerable occupants, with emergency preparedness and enhance efficiency. Human behavior during emergencies is strongly influenced by how building information is accessed and interpreted [35]. For instance, Wehbe and Shahrour [17] suggest that understanding complex building layouts and navigating key elements, such as doors, windows, exits, and stairs, is essential. Traditional methods of understanding building layout, such as two-dimensional (2D) drawings, are inefficient and expensive [23]. Similarly, printed booklets and videos have limitations that can hinder occupants' ability to learn effectively [8], such as their failure to capture occupant decision-making under pressure [20]. To address these limitations, Saini et al. [22] proposed a data-asymmetry-driven framework to predict crowd behavior in indoor spaces with multiple exits, to provide a real-time evacuation route plan. Additionally, immersive three-dimensional (3D) models significantly enhance the understanding of complex designs and support buildability more effectively than 2D drawings [38], making it easier for occupants to comprehend the building layout [35].

Specifically, Paes et al. [8] also noted that AR-based training methods can increase confidence and improve engagement during training. Although these methods enable understanding of complex building layouts, using them effectively during real emergency evacuations remains challenging. For example, regular cues and drills during emergency preparedness can increase occupant situational awareness and improve decision-making when evacuation [11]. Notably, digital dashboards and visualization aid group decision-making, enhancing clarity and accuracy [39]. Overall, integrating advanced visualization technologies into regular preparedness training can significantly improve occupants' evacuation efficiency during emergencies.

Recent training advances highlight that occupants, such as the visually impaired and those with mobility issues, face greater challenges during emergencies due to often inaccessible or inadequate signage, lighting, and smoke alarms [21,40]. A previous study estimated that over 160 million people are visually impaired, and 37 million are completely blind [40]. Therefore, it is essential to incorporate their specific needs into the design of the emergency preparedness framework and evacuation systems. However, uncertainty about the emergency and occupant location can delay evacuation.

Digital technologies provide real-time guidance, navigation, hazard detection, and customized evacuation routes for vulnerable occupants. For example, integrating IoT with AI for early detection [40] and combining it with BIM enables fire monitoring and real-time mapping, which helps guide occupants during evacuation [23]. Our review identified a limited number of studies focused on vulnerable occupants. To address this gap, we outline specific needs and technology solutions (see Table 5). Notably, visually impaired occupants need audio navigation, haptic cues and YOLO-based hazard detection. Then, mobility-impaired users require BIM-aware routing and a personalized AR route to avoid stairs. In addition, hearing-impaired individuals benefit from visual alarms, LED signage and smartphone vibration patterns.

Table 5. Digital Technology Solutions for Vulnerable Occupants.

Vulnerable Occupants	Digital Technology Solutions	Results
Visually Impaired	Smart glasses (YOLOv5 and audio alerts) AI and IoT provide real-time hazard monitoring.	[10,21,23,35–37,40]
Mobility-Impaired	BIM-based AR personalized routes by passing stair.	[4,14,17,24,25,28]
Hearing Impaired	Visual AR overlays with flashing LED exits.	[8,11,40]
Disoriented Occupants	Recommender systems using real-time IoT congestion data.	[4,11,18,25,27,28,37]

In addition, Global Positioning System (GPS) technology, such as Smart Escape using artificial neural networks (ANNs), enhances hazard prediction accuracy, including fire location and spread rate, Radio frequency identification (RFID), and sensors, enhances location tracking and route planning for the visually impaired [4,23]. Consequently, one implication is that YOLO v3 with multilevel perceptron (MLP) layers can improve image prediction, while infrared (IR) sensors can reduce response time at short distances [40]. Additionally, Saini et al. [22] note that communication failures can delay evacuations and increase occupant casualties during emergencies. To address these issues, integrating IoT and cloud computing shortens route-planning response times and enables quick updates to the remote environment. Among these, robotic guide dogs and white canes provide navigation assistance through obstacle detection, delivering more accurate navigation support [40]. Generally, integrating advanced sensing, navigation, and communication technologies can significantly improve evacuation efficiency and safety for vulnerable populations, thereby strengthening emergency preparedness.

4.7. Digital Technologies Integration

This section mainly answered Research Question 3 in several sections, including early warning systems, indoor navigation, Emergency simulations, and power outage solutions. Cross-application analyses reveal complementary capabilities. The distribution of digital technologies across various application areas, including training and education, occupant situational awareness, decision-making, evacuation, and communication (see Figure 9). The figure maps each technology to application areas. The width of the arrows represents the number of articles linking the technology to that application (e.g., BIM (n = 16)).

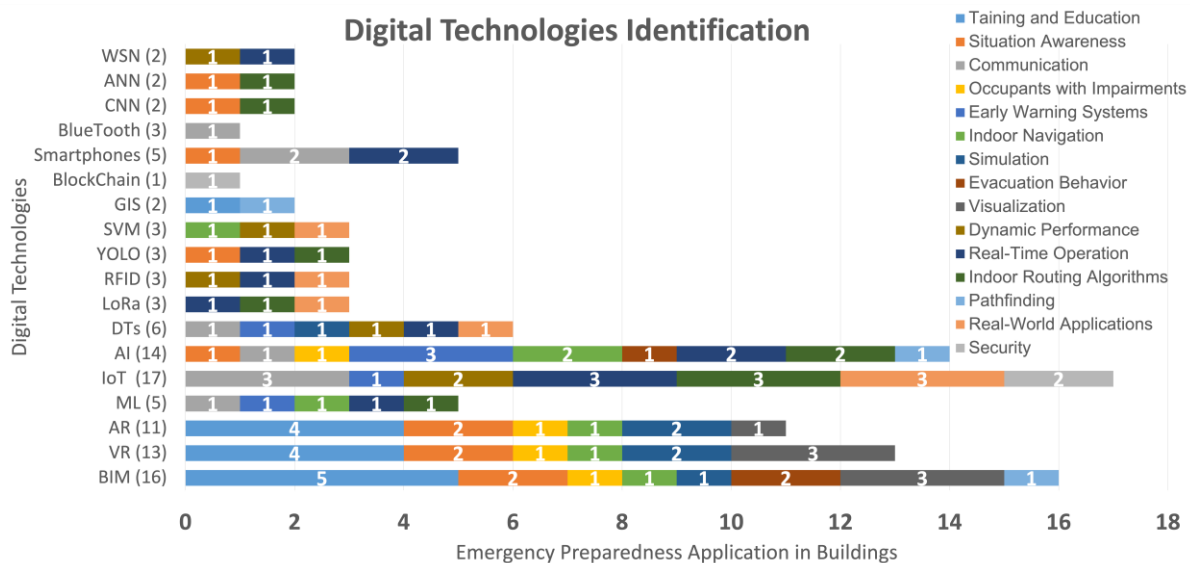


Figure 9. Digital Technologies Identification.

As shown in Table 6, the advantages and challenges of digital technologies are categorized. The study employs a multidimensional analysis of technological, occupant, and environmental factors as different aspects of digital technologies for emergency preparedness [41]. It aims to enhance occupant situational awareness [31] and decision-making [39]. Additionally, the review is particularly relevant in this context because it links technology functions (e.g., sensing, simulation, and communication) [18,25] to emergency response needs (e.g., early warning, evacuation, and coordination) [4,16]. The classification of technologies is based on their functions and the extent to which they are implemented in different emergency preparedness stages. The study describes how segmented digital technologies enhance occupant safety resilience across several key evaluation criteria.

Table 6. Evaluation of Digital Technologies in Practice.

Technology Classification	Advantages	Challenges	Key Evaluation Aspects
GIS Mapping	Visualize safe routes Resource allocation	Data security Data compatibility issues	Resource allocation effectiveness.
VR/ AR/ MR	Immersive environment Enhanced user interaction Overlay virtual elements	Initial costs User Training Motion sickness	Stress reduction features Safety resources availability Training accessibility
Mobile Apps	Emergency alerts Shelter locations	Privacy System integration	Information sharing platforms
AI(ML)	Integrate IoT data for prediction	AI biases User Training	Automated decision support
BIM	IoT for real-time updates.	Specialized training and data compatibility	Building Response Capacity
IoT	AI for emergency detection.	Sensor accuracy Reliability in extreme conditions	Accuracy
Digital Twins	Simulate hazard scenarios. Real-time simulation.	Complex setup and cost High computational requirements	User acceptance

Digital technologies interventions for emergency preparedness can be categorized into three main areas: (1) sensing and localization (e.g., IoT, WSNs, BLE, LoRa, and Radio frequency identification (RFID)) that enable continuous monitoring, navigation and indoor positioning [13,25,35,36]; (2) modeling and analytics (e.g., BIM, AI/ML, Fire Dynamic Simulation (FDS), and Agent-Based Simulation (ABS)) used for spatial simulation, hazard prediction, and route planning [17,26]; and (3) immersive training and decision-making support (e.g., VR/AR, dashboards, and DTs) for scalable training, real-time visualization, and operator assistance [15,23,36]. However, implementing these features in real-world settings is hindered by issues such as fragmented integration, insufficient large-scale validation, and common challenges, including sensor accuracy, latency, interoperability, privacy, scalability, and occupant acceptance.

As shown in Table 7, recent literature on digital technologies integration in emergency preparedness maps each technology to its specific performance contributions. BIM helps display 3D model layouts and integrates with sensors to detect emergency information, thus visualizing the emergency status [16]. IoT and AI collaborate to support occupant evacuation and enhance fire detection [17]. Then, IoT and Cloud Computing support remote occupant decision-making and situational awareness, integrated with Wireless Sensor Networks (WSNs), including Wi-Fi, Zigbee, and Bluetooth [25]. While BIM, VR, and

AR primarily focus on understanding building types and enhancing occupant learning, incorporating complementary technologies such as ML, IoT, and AI can further improve occupant situational awareness, hazard prediction, and evacuation route planning [8]. Among these, integrating BIM and IoT cameras establishes a solid foundation for real-time emergency monitoring, offering more practical and precise support than using VR/AR alone [23].

Table 7. Digital Technologies Integration and Performance.

No.	Digital Technologies Integration	Performance	Articles
1	IoT Cloud Computing Fog Computing	Decision making remotely. Occupant situational awareness and route planning. Quick response time.	[22]
2	BIM VR AR	Understand the building typology. Enhance engagement of occupant learning. Build confidence.	[8]
3	IoT ML	Collect sensing data. Emergency and evacuation route detection. Prediction of hazard area and location.	[8]
4	IoT AI	Early detection. Evacuation.	[17]
5	YOLO v3 MLPs CNNs	Emergency image prediction, classification and detection.	[40]
6	IoT BIM	Decision making. Fire monitor in evacuation.	[23]
7	AR DTs BIM AI	Improve understanding. Decision making. Interaction.	[23]
8	IoT BIM AI	Intelligent indoor safety management. Real-time hazard response.	[23]
9	AR BIM GIS	Navigation and Positioning. Indoor route network.	[37]

Additionally, convolutional neural networks (CNNs), YOLO v3, GIS, and DTs focus on specific tasks such as image-based hazard detection, spatial navigation, and monitoring during pandemic restrictions and fire hazards [42]. Other combinations, such as IoT and ML, are used to collect sensor data and predict hazardous areas [26]. Together, these integrations showcase a multi-technology framework that enhances predictive abilities, operational efficiency, and occupant safety in complex buildings.

This Sankey diagram (see Figure 10) illustrates the connections between countries, hazard types, and various technologies used to enhance disaster preparedness. The Sankey diagram highlights how multi-hazard preparedness increasingly relies on digital technologies integration rather than single-technology deployment. On the left side of the diagram, countries such as Turkey, China, India, and New Zealand are linked to hazards such as earthquakes, fires, and pandemics. On the right, these hazards are connected to advanced technological solutions, including IoT, AI, VR/AR, BIM, and sensor networks (e.g., LoRa,

WSN, RFID) [15,28,43]. The flow of connections illustrates how different nations combine multiple technologies to address specific threats, highlighting the vital role of technological convergence in strengthening disaster preparedness. While Digital Twins are widely recognized for their use in hazard management, the diagram primarily emphasizes the importance of integrating multiple technologies across various national contexts.

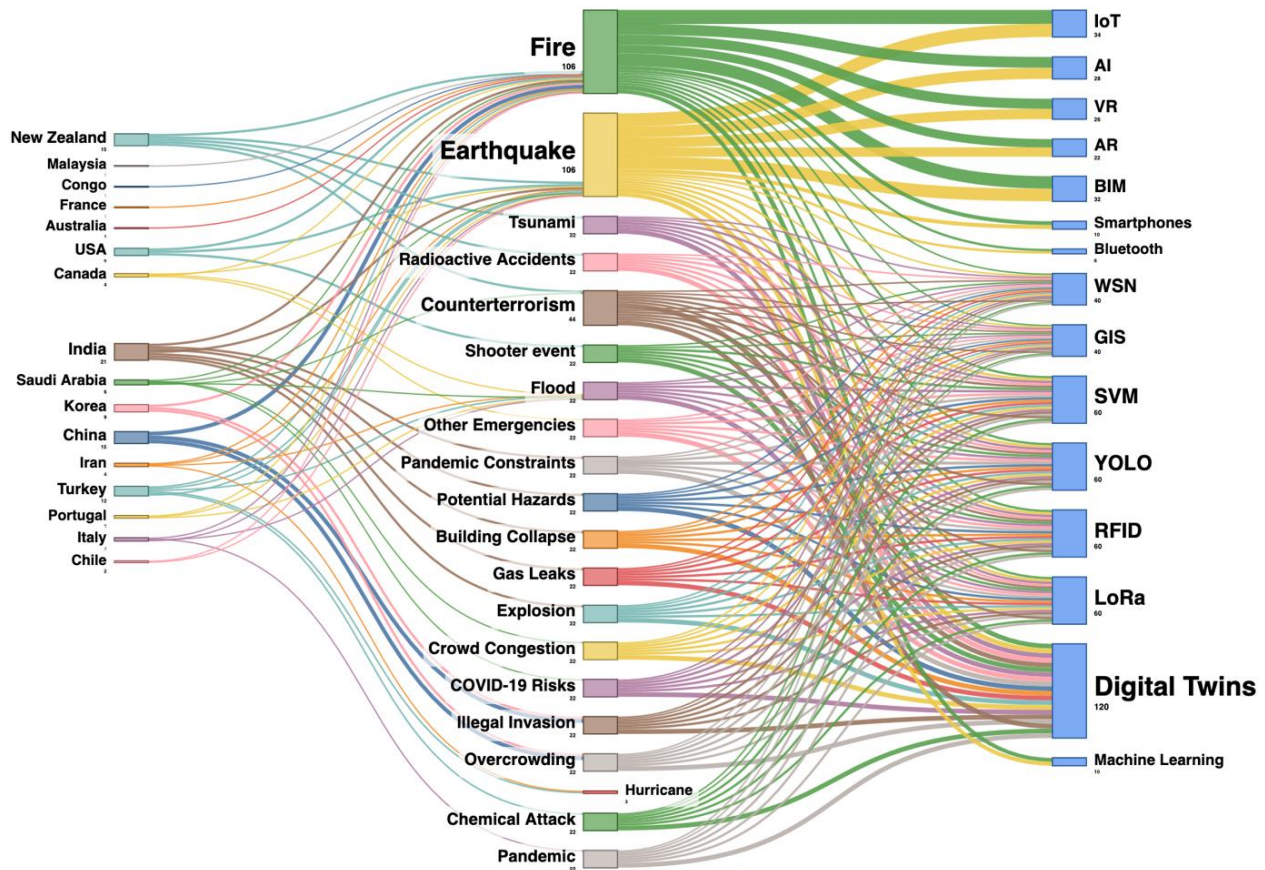


Figure 10. Sankey Diagram for Global Hazards Scenarios and Digital Technologies Application.

A proposed unified, interoperable architecture for the digital technology integration typically comprises six logical layers (see Figure 11). Furthermore, the perception layer collects heterogeneous data from IoT sensors, including RFID, BLE, GPS, and environmental monitors. Then, the network layer ensures resilient, low-latency connectivity through a converged fabric of short-range wireless (Wi-Fi, Zigbee, and 5G), low-power wide-area (LoRaWAN), and wired backhaul. Additionally, the information layer comprises an edge-cloud continuum that performs local aggregation, preprocessing, and low-latency decisions, supported by time-series and hybrid SQL storage. Notably, core analytics and modelling integrate BIM, AI/ML frameworks (including deep learning and computer vision), digital twins, and fire dynamics simulation (FDS) to enable predictive scenario analysis. These capabilities are exposed through the service layer as microservice APIs that support routing, crowd-flow optimization, and contextual alerting. Finally, the presentation and actuation layer completes the stack with immersive VR/AR visualization, interactive dashboards, and smart actuators, facilitating closed-loop, human-in-the-loop operation.

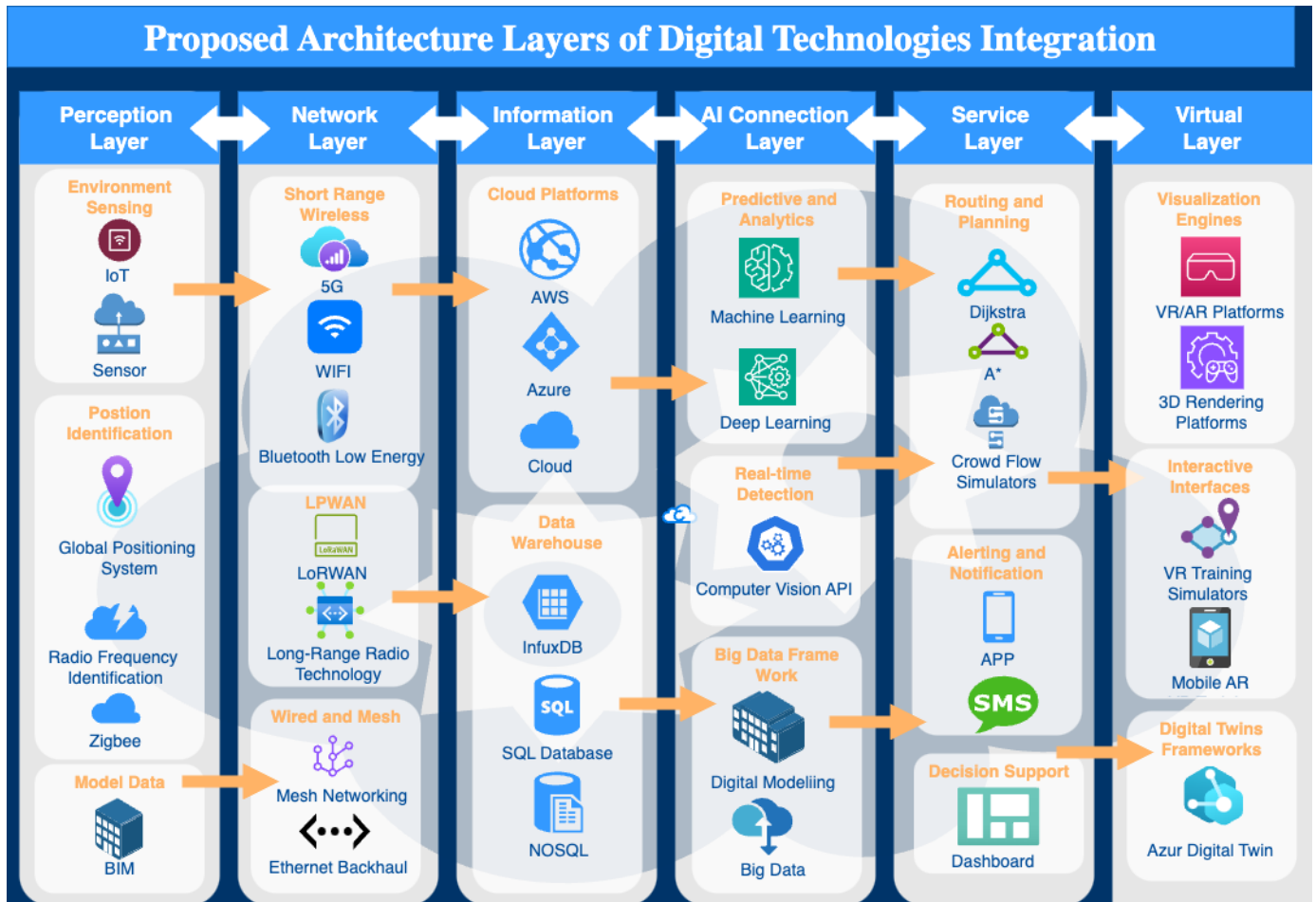


Figure 11. Proposed Architecture Layers of Digital Technologies Integration.

4.7.1. Early Warning Systems

Early warning systems (EWSs) are crucial for emergency preparedness because delays in hazard detection, slow information sharing, and inadequate guidance can directly lead to higher casualties and economic losses [44]. Incorporating digital technologies into EWS enhances occupant situational awareness and facilitates quick decision-making. Research shows that evacuation success rates significantly improve when the Available Safe Egress Time (ASET) exceeds the Required Safe Egress Time (RSET) [7,16,20,26,29] (see Figure 12). The diagram demonstrates the real-time calculation for ASET/RSET in emergency systems. Obviously, sensors send data through IoT gateways to a central server. The system decomposes the RSET into discrete phases: detection, alarm, reaction, and movement time, culminating in the total evacuation time. ASET is determined concurrently, with the safety margin defined as ASET minus RSET. Actuator outputs, including smart exit signs, emergency lighting, AR navigation, and breaker controls, are triggered by the integrated control center, which optimizes routing based on occupancy detection and crowd dynamics.

To accurately assess performance, future systems should monitor the sensor-to-alert delay, the occupant notification-to-action time, and observed egress durations, or ASET/RSET values. Evidence suggests that integrating IoT with fog and cloud computing enhances data processing, reduces evacuation times, reduces reliance on the network, and improves location awareness [22].

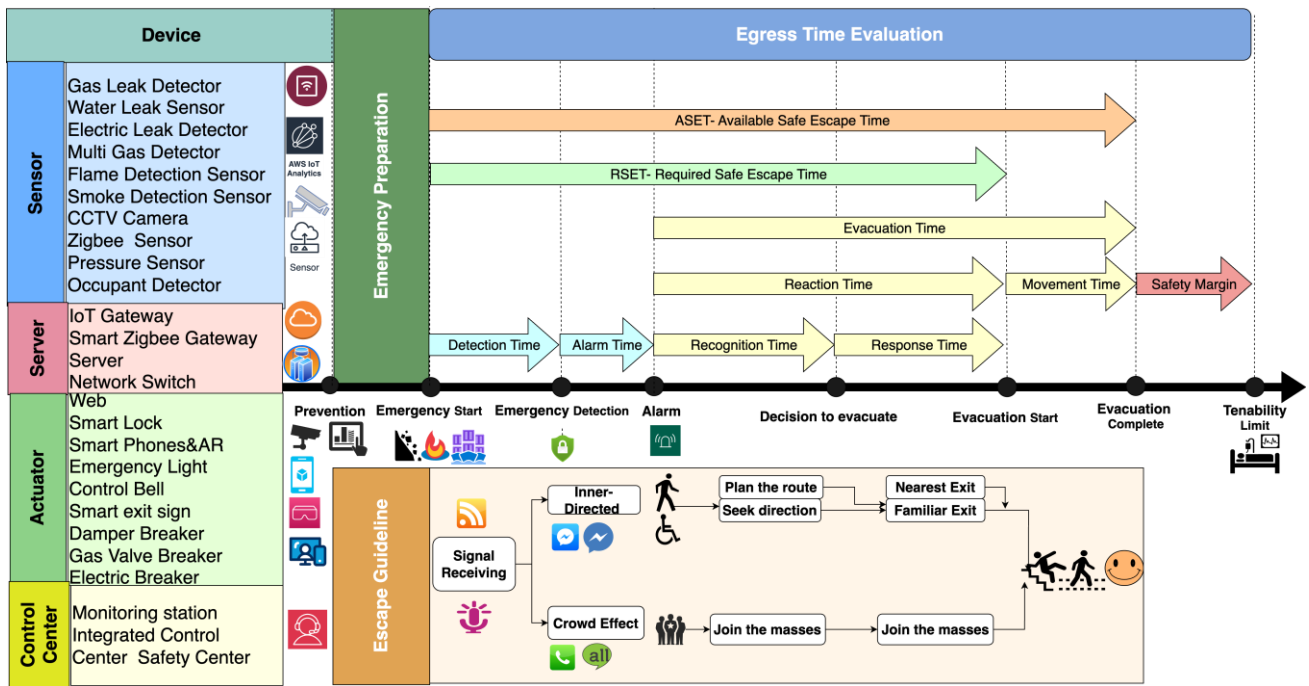


Figure 12. IoT -based Early Warning System and ASET–RSET Evacuation Timeline.

EWS effectiveness depends on four layers: sensor data collection, IoT–AI risk assessment, actuator deployment, and centralized control [13,23]. AI combines machine learning and SVM algorithms, stores real-time data and classifies safety information to deliver early warning systems for potential emergencies [4]. Additionally, BIM-IoT fire system performance validates time-critical improvements: detection time dominates at 33%, followed by improvements in evacuation time (28%), fire suppression (22%), and monitoring accuracy (17%) [16] (see Figure 13). These gains align directly with the EWS sensor collection, which accelerates detection, IoT-AI assessment enhances suppression precision, and centralized control integrates BIM spatial data to optimize evacuation routing.

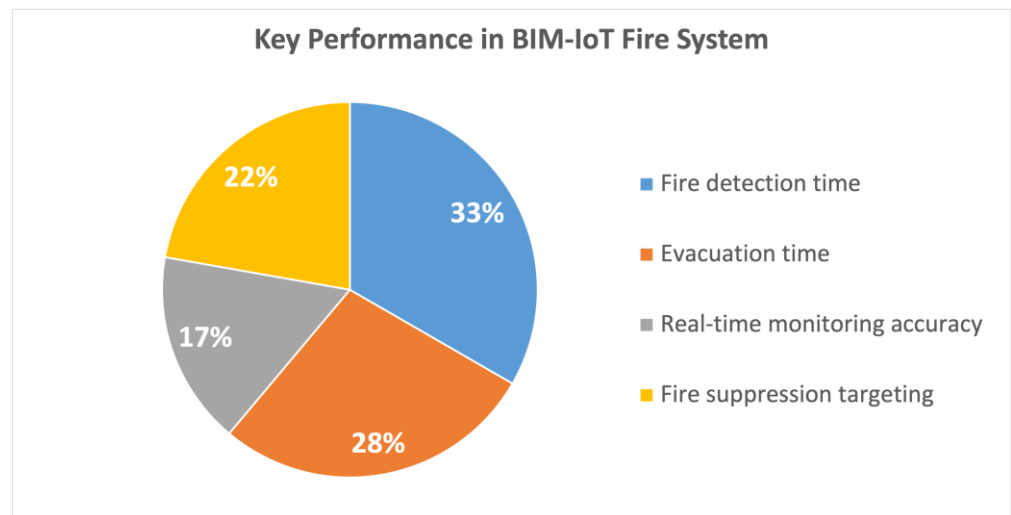


Figure 13. Distribution of Key Performance Indicators in BIM–IoT Fire System Improvement.

The actuator layer deploys smart locks and intelligent exit signage to guide occupants, while the control center layer manages the overall response through real-time monitoring and hazard detection. While most reviewed studies are simulation-based, where available, we extracted quantitative indicators (e.g., reduced evacuation times and localization errors).

However, to strengthen empirical claims, future work should extract and present these metrics in a dedicated results table and use common indicators such as mean evacuation time, ASET/RSET, latency, localization error, and accessibility success rates.

4.7.2. Indoor Navigation

Many fire-related deaths occur not because the fire spreads but because occupants cannot find their way out during an evacuation, often due to complex building layouts, blocked exits, inadequate signage, and poor lighting [13]. This highlights the need for better technology-supported indoor navigation to reduce evacuation delays and save lives. Typically, occupants rely on 2D paper documents for evacuation instructions, which are limited in their ability to help them understand building layouts and real-time locations, potentially leading to incorrect escape route choices [23]. Additionally, AR, combined with BIM on smartphones, enhances the visual experience of 3D planning by providing access to emergency information [20]. Evidence shows that AR technology, such as optical-see-through (e.g., Microsoft HoloLens) and video-see-through devices (e.g., smartphones and tablets) equipped with infrared sensors, can improve indoor navigation by mapping 3D buildings [8]. Moreover, AI technologies integrated with sensors can predict hazard locations, assess the situation, and guide occupants to safe evacuation routes [18].

Numerous studies have shown that digital technologies support real-time intelligence services and evacuation route optimization (such as A* and Dijkstra algorithms) by incorporating human factors to enhance adaptability during emergencies [18,37]. According to these studies, Dijkstra's algorithm is recognized for its performance, flexibility, and the absence of a distance function requirement. Additionally, the IoT and ML technologies integration enables the collection of sensing data, emergency detection, and prediction of emergency locations to identify the best evacuation routes [17]. It is widely accepted that DTs, AR, and AI technologies create immersive environments and help predict the most effective emergency evacuation routes [23]. Therefore, combining immersive visualization, intelligent algorithms, and real-time sensing improves evacuation efficiency and reduces delays in complex buildings.

4.7.3. Emergency Simulations

Wehbe and Shahrour [17] emphasized that the Fire Dynamic Simulation (FDS) is crucial for predicting fire spread and determining evacuation routes. They also demonstrate that both FDS and Agent-Based Simulation (ABS) can assist in estimating evacuation times by offering physical and behavioral perspectives on emergencies. Additionally, they integrate with BIM and IoT to display simulations and visualize multi-level buildings and 3D layouts, ensuring that the predicted fire spread and evacuation routes align with real-world geometry [17]. Additionally, the AI-based simulation study helps analyze the relationships among fire location in a hospital, occupant health, crowd movement, and building layout [14]. These combined simulation approaches enable real-time scenario analysis and enhance communication of evacuation plans through dynamic, data-driven inputs.

4.7.4. Power Outage Solutions

Power outages during emergencies can severely disrupt evacuation, communication, and life-safety systems, highlighting the importance of rapid restoration and the maintenance of continuous essential services [13,25]. LoRa operates at lower frequencies, providing more reliable connectivity than Wi-Fi for multi-layered emergency data [7,16,17,25,26]. RFID, Bluetooth Low Energy (BLE) unmanned aerial vehicles (UAVs), and non-intrusive load monitoring (NILM) technologies provide fallback localization when Wi-Fi fails [13,18]. Additionally, GPS provides more accurate positioning outdoors. Then, Wireless Sensor Networks (WSNs) typically have shorter transmission ranges and are designed for local,

high-frequency data transfer aimed at real-time processing and monitoring [25]. Thus, integrating technologies such as BLE, UAVs, NILM, WSNs, and LoRa improves the stability and compatibility of internet connections in buildings, enhancing power resilience.

5. Discussion

5.1. Proposed Framework

The review employs a multidimensional analytical framework grounded in critical thinking [45] and digital technologies integration [23,26,46]. The framework considers technological, occupant, and environmental components as interconnected dimensions of emergency preparedness (see Figure 14). Originally adapted from innovative building practices, the guidelines suit this context by linking technology functions (e.g., sensing, simulation, and communication) [7,13] to emergency response needs (e.g., early warning, evacuation, and coordination) [47]. Compared with other studies [48–50], the current review’s findings suggest that digital technologies should be evaluated based on their technical effectiveness and their ability to meet occupants’ needs.

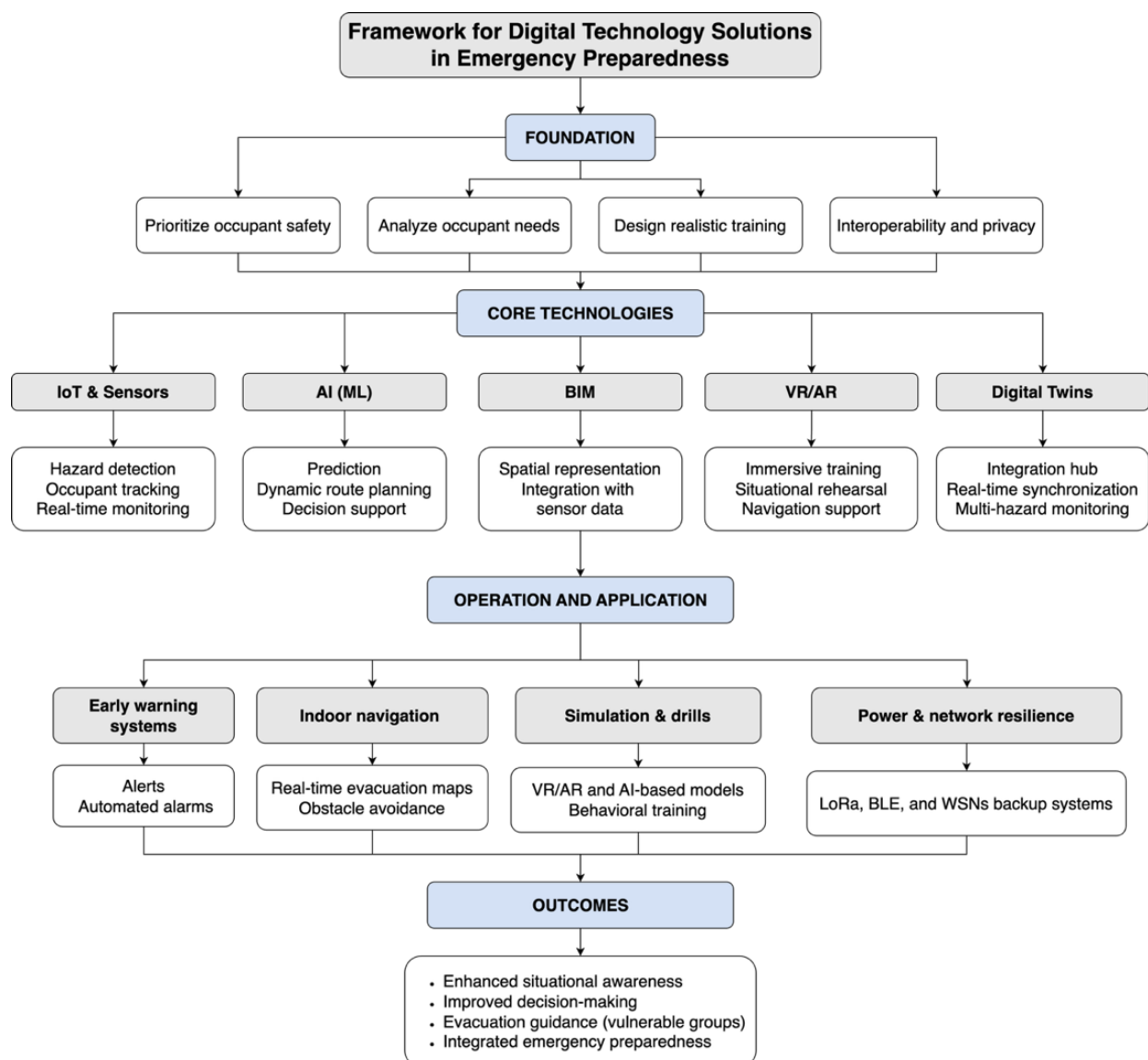


Figure 14. Proposed Framework for Digital Technology Solutions in Emergency Preparedness.

The proposed Framework for Digital Technology Solutions in Emergency Preparedness clearly answers Research Question 1 in identifying current digital technologies. VR/AR provides immersive training, IoT improves hazard detection and occupant tracking, and BIM and AI enhance occupant situational awareness through visualization, predictive modeling, and data-driven decision-making. DTs are an integrative platform compatible with other technologies such as IoT, AI, and AR to create an intelligent, visualized, and adaptive system.

This framework also addresses Research Question 2 by highlighting the challenges it poses. DTs facilitate multi-hazard monitoring, improve data interoperability, and safeguard privacy by visualizing behaviors rather than through direct surveillance. Additionally, combining VR/AR training ensures that technological solutions go beyond simulations, improve communication, are tested in real-world scenarios, and, when combined with AI and data fusion, can also enhance decision-making quality. Furthermore, utilizing DTs is a missed opportunity for real-time synchronization between physical and virtual systems.

For Research Question 3, digital technologies integration in BIM, IoT, AI, AR/VR, and DTs clearly shows benefits for early warning, navigation, training, and evacuation. Previous studies have shown that NASA was the first to utilize Digital Twin technology for predictive maintenance [36]. DTs can serve as a compatible platform for integrating several technologies, such as BIM, IoT, and AI, continuously extending BIM to enable ongoing monitoring and visualization [16] and protecting occupants' privacy by using digital figures instead of direct video cameras [42]. By continuously extending BIM capabilities, DTs enable persistent monitoring of emergencies, occupant density, and hazard propagation [16]. The integration enables scenario-based evacuation planning that automatically updates as IoT sensor data reflects changing conditions, effectively bridging the gap between static building models and dynamic emergency environments.

The limitation of the current literature is the scarcity of large-scale field trials. We recommend that future work: (1) conduct pilot deployments in operational buildings (universities and hospitals), (2) use before/after designs to measure concrete impacts (evacuation time, and ASET/RSET), and (3) consider initial costs and apply them to existing buildings as well as upgrades.

5.2. Digital Technologies Support for Vulnerable Occupants

Many emergency preparedness studies implicitly assume able-bodied occupants, yet vulnerable populations, such as people with disabilities, older adults, and children, have distinct mobility, perceptual, and decision-making characteristics. These differences significantly affect evacuation efficiency and remain insufficiently addressed in existing digital emergency preparedness research.

The reviewed literature indicates that vulnerable occupants have distinct and actionable needs that require technological solutions rather than one-size-fits-all approaches (see Table 8). For occupants with disabilities (including mobility, sensory, and cognitive impairments), key requirements are accurate localization, pathfinding, and communication. Importantly, digital responses include IoT-enabled real-time position awareness, BIM-based accessibility routing to update egress paths, and alerts (e.g., visual indicators and haptic signals) to ensure messages are perceivable. Additionally, elderly occupants typically have reduced walking speed, limited tolerance for complex interfaces, and higher anxiety under stress. Thus, effective supports identified in the literature include AI-based adaptive routing and push notifications designed to enhance cognitive ease, helping occupants identify age-related bottlenecks. Next, children are vulnerable occupants whose spatial cognition and risk judgement are still developing and who often rely on caregivers' guidance. The evidence shows that AR wayfinding, using simple visual cues, through VR serious games

to build familiarity through repeated, safe rehearsal, and visual guidance rather than traditional instructions, is effective. Together, these findings show that inclusive evacuation systems must combine sensing, adaptive analytics, and multimodal presentation layers (see Table 5 and Figure 11) so that technology stacks can be configured to meet the specific physical, perceptual, and cognitive needs of each vulnerable group.

Table 8. Summary of Vulnerable Occupants' Needs and Supporting Digital Technologies.

Vulnerable Occupants	Key Needs	Supporting Digital Technologies
Visually Impaired	<ul style="list-style-type: none"> • Non-visual orientation and obstacle detection. • Indoor localization. • Reliable audio alerts. 	<ul style="list-style-type: none"> • IoT-based indoor localization • Computer-vision hazard detection (e.g., YOLOv5) • Audio navigation systems.
Mobility-Impaired	<ul style="list-style-type: none"> • Step-free routes. • Vertical-transport availability. • Longer travel time allowance. 	<ul style="list-style-type: none"> • BIM-based accessibility routing algorithms. • Elevator status sensors with IoT. • DTs route simulation. • AR route visualization.
Hearing Impaired	<ul style="list-style-type: none"> • Visual or tactile alarm. • Synchronous alerts. • Visual instructions. 	<ul style="list-style-type: none"> • LED signage. • Smartphone notifications. • Haptic alerts.
Disoriented Occupants	<ul style="list-style-type: none"> • Simple guidance. • Reduced cognitive load. • Caregiver coordination. 	<ul style="list-style-type: none"> • Low-complexity guide. • Multimodal alarm. • Directed group guidance.
Elderly Occupants	<ul style="list-style-type: none"> • Slower mobility. • Reduced complex interfaces. • Health monitoring. 	<ul style="list-style-type: none"> • AI-driven path finding. • Simplified notification digital-twin dashboards. • Wearable health sensors.
Children	<ul style="list-style-type: none"> • Limited spatial cognition. • Dependence on caregivers and parents. • Need for repeated cues. 	<ul style="list-style-type: none"> • AR wayfinding. • Gamified VR serious games for procedural training • Visual signage and child-friendly audio alarm.

Despite these advances, the literature lacks large-scale empirical validation in real-world operational buildings with vulnerable occupants. Ethical constraints, safety considerations, and recruitment challenges limit the scope of experimental studies. There is a need for future interdisciplinary and field-based research.

6. Conclusions

As a systematic literature review, this study synthesizes evidence reported in existing empirical and simulation-based studies rather than conducting primary experiments. This review highlights the use of digital technologies for emergency preparedness to enhance occupant safety in buildings, based on 31 journal articles published between 2015 and 2025. The study reveals that BIM, IoT, and AI are the most frequently utilized technologies, often combined to enhance occupant situational awareness, predict hazards, and support evacuation. VR and AR are widely employed for immersive training and navigation.

Similarly, DTs remain underexplored in emergency preparedness despite their strong potential for real-time synchronization and adaptive monitoring. These findings suggest that integrating IoT with BIM, AI, and sensor networks is the most promising approach for real-time hazard detection, occupant monitoring, and multi-hazard response.

There are still some limitations of these technologies for emergency preparedness. First, issues with interoperability, sensor accuracy, latency, and computational demands compromise the reliability of technology during real-world emergencies. Then, human factors, such as limited training and varying levels of technology acceptance, remain unpredictable and continue to limit system effectiveness. Additionally, privacy concerns and high implementation costs hinder widespread adoption. These barriers show that while technology can improve emergency preparedness, it must be adaptable and consider the specific context.

This review highlights several research gaps, including the need to account for human behavior when designing emergency preparedness systems, particularly for vulnerable occupants. Another gap is the lack of incorporation of advanced digital technologies into emergency planning, as discussed in the articles. Additionally, location technologies, such as WSN, LoRa, RFID, BLE, ZIGBEE, and sensors, can support navigation and communication during power outages or network failures. However, further real-world testing is necessary to confirm their effectiveness.

Future research should focus on three key areas: firstly, a deeper understanding of how human behavior and decision-making influence evacuation outcomes, particularly in relation to the use of digital technologies. Second, as sensor-based monitoring becomes more prevalent, research must address concerns regarding privacy, trust, and user acceptance. Third, large-scale field trials and real-world experiments are crucial for validating system effectiveness beyond simulations. Overall, while combining SVM, ANN, and BLE can provide solutions during emergencies, future innovations could lead to more practical, automated options. Highlighting the role of Digital Twins as integrated platforms is crucial. DTs can combine IoT data, BIM models, AI, and immersive VR/AR environments into a unified system that supports real-time visualization, predictive decision-making, and adaptive evacuation planning. Advancing this area of research could enable DTs to play a critical role in emergency preparedness, providing flexible responses to a range of hazards.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/buildings16040856/s1>, Table S1: PRISMA 2020 checklist. This supplementary file provides the PRISMA 2020 checklist used to ensure transparency in the systematic review process. It outlines the reporting items across all sections of the manuscript, including the title, abstract, methodology, results, discussion, and other relevant information. The checklist supports standardized reporting guidelines and improves the clarity of the review.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Summary of Articles.

NO.	Authors and Years	RQ1	RQ2	RQ3
1	[51]	Virtual Reality Serious Games (IVR SGs) for indoor evacuations, focus on safety knowledge, self-efficacy, and engagement in multi-phase emergency training program.	No control group. Lack of knowledge retention assessment.	Earthquake: AR, VR and BIM for safety awareness, tracking and recognizing.
2	[20]	AR in building evacuation, in training, navigation, and simulation, identifying validation, and SWOT analysis.	Cost of investment. AR in the early stages. Limited in brightness and color range.	Fire, Earthquake, Tsunami, Radioactive Accidents: AR/VR, BIM and smartphone for navigation and evacuation.
3	[35]	Sensor-based IoT, BIM, VR, and AR improve fire safety by enhancing occupant situational awareness. Data aids in quick fire location.	Lack of capability to update real-time information. Hard to make BIM in advance. Limitation of AR real-time route finding.	Fire: BIM, Bluetooth, IoT and sensors for fire monitoring. IoT, BIM, VR, and AR for safety and efficiency. Computational Fluid Dynamics (CFD): simulation training. Radio Frequency Identification (RFID): accuracy positioning.
4	[23]	DTs in fire safety, exploring opportunities, and potential applications to guide future practices.	Data security, accuracy and latency. Sensor reliability. High initial costs. Lack of knowledge in DTs. User acceptance.	Fire: DTs (simulation & evacuation), BIM-based smart system (early fire detection and identify evacuation routes), blockchain (security) and IoT (monitoring and predictive security).
5	[13]	Evaluating advanced localization technologies: crowd sensing, 6G, UAV, RF, and NILM.	Data privacy and accuracy. Communication latency. Complexity and stability. Coverage and detection.	Earthquake, Flood, Fire: AI, UAV, RF, Non-intrusive load monitoring (NILM), RFID, Zigbee and 6G for localization.
6	[42]	This study presents a VR–DTs framework for precise, privacy-safe social distancing monitoring and AI training with synthetic data, reducing latency by streaming only extracted info.	Computer vision validation in large-scale datasets. Real-time data update.	Pandemic: DTs (accuracy and privacy for social distancing monitoring and training), AI(YOLOv3) and VR (simulation to create virtual office space to upload real-time location data). Computer vision method to measure social distance. CNNs: social distancing detection.
7	[18]	Indoor routing system for complex environments manages crowd density, predicts paths, and enforces social distancing using Dijkstra's and A* algorithms.	Sensor accuracy. Emergency environment changes. Obstacles affect internet communication.	Fire, Crowd and Pandemic: AI & IoT (real-time data update) & Wi-Fi & WLAN, Bluetooth low energy (BLE) & RFID (Indoor navigation).
8	[7]	Escape algorithms offer safe rescue guidance in fire emergencies.	Difficulty to create real-world validation Focused limited only on fire.	Fire: IoT real-time remote system for fire detection & Smart gateways, sensors, and actuators & AR for visualization and hazard classification.
9	[21]	YOLOv5m for real-time indoor fire monitoring, and combining detection, and navigation for occupants.	Incorrect detection and wrong alarm. Difficult to collect real world data.	Fire: AI(YOLOv5+DL) & IoT & smart glasses for real-time monitoring, early fire detection, and notification for system in visually impaired people.

Table A1. Cont.

NO.	Authors and Years	RQ1	RQ2	RQ3
10	[10]	AR navigation offering better crossroads evaluation after stairs and faster responses when evacuation.	Devices limitation smart phone only. Demographic limitation.	Fire: AR navigation and eye-tracking system aids fire detection, and BIM for visualization.
11	[8]	Optical see-through AR fire safety training is compared with video and XR to evaluate knowledge retention, motivation, and self-efficacy.	Lack of real-world VR experience. High Cost and time requirement in AR development.	Fire, Terrorist attack, and Earthquake: AI & AR: hazards detection, training, and visualization. IoT & ML: predicting hazard situation.
12	[11]	A virtual fire evacuation drill that integrates BIM, and a physics engine collision model, validated through human experiments.	Lack of control over human behavior. Lack of real-world hazards experience.	Fire: BIM, computational fluid dynamics (CFD) & VR for smoke visualization. GPS: visual impaired person solutions.
13	[40]	IoT and ML for a smart cane with apps assist visually impaired navigation, using YOLOv3 and MLP for obstacle detection and classification.	Incorrect detection and ML training in crowd environment. Not enough sensors for items detection. Wearable travel aid design challenges.	Fire & Other hazards: YOLO v3 for detection & visual aid technologies (e.g., MLPs, Fast R-CNN, White cane and guide dogs) for visual impaired improvement.
14	[37]	The indoor evacuation system integrates BIM, GIS, Wi-Fi, Pedestrian Dead Reckoning (PDR), and AR visual guidance to navigation.).	Relies on Wi-Fi, 3D, and software. High cost in AR development.	Fire, earthquake, flood, and hurricane: VR/AR improves evacuation & KNN for localization & Dijkstra (pathfinding). Mesh network/ Triangulated Irregular Network (TIN)/System Usability Scale (SUS) (Simplify the network & resolution in open ground).
15	[36]	DT-based indoor safety system to provide recommendations for safety management.	Lack of method for indoor safety management.	Fire, illegal invasion, and overcrowd: IoT and BIM for obtaining indoor hazard detection. SVM for processing data in levels of danger, and LoRa for wireless communication.
16	[16]	Intelligent and resilient fire safety systems enhance management to reduce fire damage and improve occupant safety.	Cost of installation. Cybersecurity.	Fire: Fire dynamics simulator (FDS), BIM, IoT, ML and DTs for sensors and detectors to enhance occupant situational awareness.
17	[4]	Smart Escape is a real-time, intelligent mobile evacuation system for fire and emergencies.	Limitation of RFID for real-time location. Rely on network connection.	Fire, and terrorist attacks: ANN, RFID and Bluetooth.
18	[17]	Smart building-based fire evacuation system to address occupant evacuation solutions.	Technology relies on technology. High cost.	Fire: BIM, Bluetooth, IoT and AI to improve occupants' evacuation and collect data. Wireless networks for communication. Fire Dynamic Simulation (FDS) & Agent-Based Simulation (ABS) for estimating evacuation time.
19	[25]	Hybrid emergency evacuation approach to calculate real-time evacuation paths.	High power requirement in Internet. High cost.	Fire, Earthquake, Flood, and Terrorist Attack: WSNs, Dijkstra algorithms, ZigBee, Bluetooth, IoT and Cloud Computing for evacuation paths monitor, low consumption, low-cost, and low energy.

Table A1. Cont.

NO.	Authors and Years	RQ1	RQ2	RQ3
20	[22]	Intelligent evacuation system optimizes sensing for real-time hazard prediction.	Network security and Latency. Unpredicting human behavior.	Fire, Earthquake, and Structure failure: AI (SVM & A*), IoT, fog and cloud computing for evacuation.
21	[27]	AR allows 3D visualization of spatial context to enhance learning cognitive mapping.	Rely on phone connection.	Fire, Earthquake, and terrorist attack: AR (HoloLens) provides 3D visualization.
22	[19]	IVR in earthquake safety training assesses how education, forecasting, and simulation affect responses.	Simulation lack of earthquake shaking.	Earthquake, and fire: VR simulations and immersive evacuation.
23	[28]	Innovative approach to enhance occupant behavior predictability by providing real-time information on the best evacuation routes.	Lack of information for occupants. Unclear route findings.	Fire: FDS and ML to reduce evacuation time.
24	[29]	Database to improve simulation accuracy and suggests design strategies for buildings.	Limitation of analytical data.	Fire: Simulation, Pathfinder and ML to reduce evacuation time.
25	[30]	The AR mobile app provides a realistic training environment for university stakeholders, enhancing occupant situational awareness and satisfaction.	Lack of control. Time consuming for 3D models.	Fire, chemical attack, earthquake: Rescue Me (AR for emergency situations). Smart glasses: Tsunami drill.
26	[15]	Implement a BIM-GIS asset management system at an Italian university to enhance user experience and optimize resources.	Rely on internet and data security.	Fire, pandemic, flood, and earthquake: BIM, GIS, AI, IoT, and DTs are used for visualization, building dynamics, security, and automatic hazard response.
27	[26]	IoT for fire evacuation, evaluating its real-world effectiveness and to advance intelligent fire protection systems.	Limitation of sample size. High-rise building evacuation challenges	Fire: IoT in real-world fire scenarios to enhance escape procedures, reduce reaction time, and improve occupant safety.
28	[43]	VR for evaluating building layouts, enabling parametric route analysis and collecting evacuation behavior and eye movement data.	Lack of temperature experience. Limitation of occupants for students only.	Fire: VR, Pathfinder, and FDS for fire evacuation, occupant behavior, and attention.
29	[14]	Multi-agent system guides fire evacuation with routes, and equipment instructions, evaluating phased evacuation and ramp benefits for mobility issues.	Lack of knowledge. Various occupant health status.	Fire and unpredictable hazards: AI, Agent-Based Modeling (ABM), and Safe Gress for fire location, modeling, and occupant interactions.
30	[24]	Developing evacuation plans using pedestrian simulations based on their environment.	No real-time interaction.	Fire and earthquake: Computer simulation and Pathfinder help to analysis human behavior and Early warning systems.
31	[31]	Define fire response goals by integrating BIM and IoT, then develop sequence and behavior data models.	Only experts.	Fire: BIM, GIS and IoT in integrated systems to provide information, better communication and enhance occupant situational awareness.

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