

SURVEY

Evaluating Smart Building Features for Fire, Electrical, and Life Safety: A Rapid Human-LLM Framework for Literature Review and Research Mapping

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ABSTRACT The rapid integration of smart technologies into modern buildings is fundamentally transforming fire, electrical, and life safety (FELS) systems. This paper introduces a hybrid Human–Large Language Model (LLM) framework designed to efficiently conduct large-scale literature reviews, systematically map existing research, and identify critical knowledge gaps in smart building safety. Leveraging advanced LLMs for high-throughput summarization, topic modeling, and gap analysis, combined with expert validation, this method ensures both scalability and domain-specific rigor. The study analyzes 1,409 publications retrieved from Scopus, culminating in a refined corpus of 83 high-quality articles categorized into nine thematic clusters, including advanced sensing technologies, automation, enhanced connectivity, digital twins, cybersecurity, standard compliance, sustainability, specialized applications, and decision-making in disaster response. Detailed gap analyses reveal significant challenges related to real-world validation of AI-based systems, interoperability among IoT devices, cybersecurity vulnerabilities, and the need for dynamic evacuation and hazard modeling. The resulting knowledge map and research roadmap provide actionable insights for researchers, practitioners, and policymakers aiming to advance safer, smarter, and more resilient built environments. The proposed framework demonstrates how AI-assisted methodologies can accelerate knowledge synthesis while preserving analytical depth, offering a scalable solution for rapidly evolving interdisciplinary research domains.

INDEX TERMS Smart buildings, fire safety, disaster response systems, knowledge map, large language models (LLM), research gap analysis, AI-assisted literature review.

I. INTRODUCTION

Fire and life-safety systems remain the first line of defense against building emergencies. However, their protective role is being significantly reshaped by the proliferation of smart, interconnected devices. Standalone smoke and

carbon monoxide (CO) alarms already demonstrate substantial benefits; homes equipped with functional smoke alarms experience approximately 60% lower fatality rates compared to those without alarms [1]. Yet, contemporary buildings increasingly integrate complex technologies, such as Internet-of-Things (IoT) networks, artificial intelligence (AI)-enhanced analytics, cloud computing platforms, and digital twins, into various building systems, including

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fire alarm panels, suppression equipment, HVAC systems, security infrastructure, and occupant-communication networks [2], [3], [4].

The authors emphasize that this accelerated integration of smart technologies presents both significant opportunities and notable risks. On one hand, advancements in sensors powered by AI-driven computational methods and rapid discovery of novel materials have enhanced hazard detection accuracy, facilitated predictive maintenance, and encouraged manufacturers to develop increasingly sophisticated and miniaturized devices [5], [6], [7]. On the other hand, this technological complexity has introduced new challenges, including cybersecurity vulnerabilities, interoperability issues, and ambiguity in regulatory guidance [8], [9], [10]. Recognizing these critical factors, the Society of Fire Protection Engineers (SFPE) Foundation launched in 2022 the Grand Challenges Initiative (GCI) to develop a comprehensive strategy for research, education, and outreach focused on four priority areas [11]. These topics are not exclusive to fire engineering but represent urgent global challenges where fire safety science and engineering can make meaningful contributions to issues affecting billions of people worldwide. One specific research need identified through the GCI is the development of recommendations to optimize integrated smart systems in buildings. To achieve this, it is essential to establish a thorough understanding of the current landscape of smart and connected devices and systems as they relate to fire, electrical and life safety, as well as affiliated systems (FELS). This project, sponsored by the Fire Protection Research Foundation (FPRF), aims to address this gap and serves as an initial step in response to the initiatives outlined in the GCI white paper titled “Digitalization, Artificial Intelligence, and Cybersecurity” [12].

Considering the rapid and diverse growth of the scientific literature, the authors highlight that conventional, purely manual literature reviews are increasingly inadequate. The traditional approaches struggle to capture emerging developments in areas such as [4], [13], and [14]. Recognizing these challenges, the authors of this paper propose a hybrid of Human and Large Language Models (LLM) method for conducting large-scale literature reviews focused specifically on smart features in buildings and their impact on FELS. The need for this survey arises from the fact that research on smart building technologies for fire, electrical, and life safety is expanding rapidly yet remains fragmented across multiple domains, including artificial intelligence, Internet of Things (IoT), automation, sensing, cybersecurity, and digital twins. Most studies focus on isolated technologies, with limited attention to holistic integration, standardized interoperability protocols, or cross-cutting issues such as cybersecurity resilience and user accessibility. This survey also captures the technological shift from legacy fire sensors, typically relying on single-parameter detection (smoke, heat, or flame) with fixed thresholds, minimal communication capabilities, and no self-diagnostics, to modern smart sensors. These newer devices use multi-parameter sensing (e.g., smoke, heat, CO,

CO₂, flame spectra), apply AI-driven analytics to minimize false positives, and adapt their sensitivity to changing environmental conditions. This technological progression is illustrated in Fig. 1, which outlines the role of AI across different fire detection modalities, and Fig. 2, which contrasts the key features of conventional fire sensors with those of modern smart sensors.

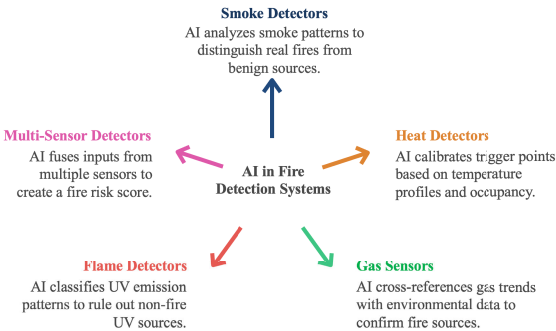


FIGURE 1. AI in Fire Detection Systems: Roles of AI across different sensor modalities.

Conventional Sensors	New Smart Sensors
Single-parameter detection	Multi-parameter sensing
Fixed threshold triggers	AI-driven analytics
Limited communication	Networked integration
No self-diagnostics	Self-diagnostics and predictive maintenance
Minimal environmental adaptability	Environmental adaptation
No remote monitoring	Geo-tagged and zoned alerts

FIGURE 2. Comparison between conventional and new smart fire sensors.

By adopting a hybrid human–LLM approach, this survey synthesizes literature from diverse technical areas, assessing both awareness and adoption of smart sensor features in smart buildings. Comparing current practices with these advanced capabilities enables the identification of deployment gaps and future research directions to guide the development of robust and resilient smart-building FELS systems. This hybrid approach strategically integrates the computational efficiency of LLMs for rapid summarization and clustering of extensive literature datasets with the critical oversight provided by human experts who ensure accuracy, relevance, and domain specificity.

Unlike fully automated techniques, which may suffer from inaccuracies or lack contextual nuance, or traditional manual approaches that are resource-intensive and slow, this method is designed to provide a balanced solution [14], [15], [16]. It rapidly identifies core themes, synthesizes comprehensive textual summaries, and performs detailed gap analyses in a significantly reduced time frame. Furthermore,

due to the dynamic and continually evolving nature of literature in fields involving artificial intelligence, sensor technologies, cybersecurity, and building automation, the method is explicitly designed to be iterative and repeatable, enabling efficient updates as new research emerges.

Crucially, human intervention at strategic points ensures rigorous validation and interpretation of automated outputs [17]. This enables not only a thorough understanding of current research gaps and future opportunities but also the creation of structured knowledge maps. Such knowledge maps facilitate clear and actionable research roadmaps, providing researchers, industry professionals, and policymakers valuable guidance on prioritizing future studies and interventions in smart-building safety research. The primary objective of this study is to systematically identify key research themes, critical knowledge gaps, and potential directions for future research within the domain of smart building technologies impacting fire, electrical, and life safety. To achieve this objective, the authors conducted a structured literature review utilizing the Scopus database, selected due to its extensive coverage of peer-reviewed scientific literature across engineering, technological, and safety-related disciplines. The scope of this paper explicitly focuses on smart or connected devices, emerging technologies, and integrated systems associated with fire detection, electrical safety, life safety, and emergency response within modern buildings. Relevant literature was identified using carefully selected keywords related to these disciplines. In addressing the challenge posed by the rapidly evolving and expansive literature in this domain, the authors adopted a hybrid Human LLM framework. This method enabled rapid summarization and thematic clustering of the retrieved publications, supplemented by expert validation to ensure accuracy and relevance. Through this structured approach, the study identified several core thematic areas, including advanced sensing technologies, automation, enhanced connectivity and integration, standard compliance management, digital twin applications, and decision-making frameworks during emergencies. By highlighting and addressing key knowledge gaps particularly those concerning cybersecurity vulnerabilities, interoperability challenges, validation of AI-driven technologies, and the adaptability of current standards, this study provides a clear and evidence-based research roadmap. The insights derived from this systematic approach aim to inform and guide stakeholders, including researchers, facility managers, technology providers, emergency responders, and policymakers, in their collaborative efforts to develop safer, smarter, and more resilient building environments. Detailed analysis and comprehensive discussions related to these findings will be presented in subsequent sections of the paper. Specifically, the major research contributions from the developed hybrid Human-LLM model are:

- **Rapid Approach:** The proposed framework leverages the computational efficiency of LLMs for summarizing and clustering large literature corpora, significantly accelerating the traditional literature-review process.

- **Iterative Updates:** Designed specifically for dynamic and rapidly evolving research fields, this approach enables efficient re-analysis and updating of literature as new studies emerge, while preserving domain-specific accuracy through human oversight.
- **Rich Summaries and Gap Analysis:** The hybrid method moves beyond traditional bibliometric metrics to generate detailed textual summaries, allowing for comprehensive gap analysis and clear identification of unresolved questions within the research domain.
- **Knowledge Map Creation:** By systematically clustering literature into clearly defined thematic categories, this method produces a structured knowledge map, which facilitates immediate identification of relationships between different research topics and highlights emerging research opportunities.
- **Real-World Application to Smart Building Technologies:** The developed method is specifically demonstrated through application in the domain of smart building technologies impacting fire, electrical, and life safety, providing actionable insights and guiding future research directions for stakeholders in this critical area.

II. BACKGROUND AND RELATED WORK

Recent advancements in smart sensing and automation technologies have significantly reshaped FELS strategies within building infrastructures. The integration of advanced sensing methods, Internet-of-Things (IoT) frameworks, AI, and real-time data analytics has enabled the creation of highly responsive and adaptive safety systems, enhancing hazard detection, prediction, and emergency response capabilities [17], [18], [19]. To provide a comprehensive foundation for understanding these technological advancements, the authors of this paper, specialists in building construction, computing, and electrical and civil engineering, conducted an in-depth investigation of market-leading smart sensor manufacturers and thoroughly reviewed key scientific literature. This rigorous selection process, following Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, resulted in the identification of several notable studies that illustrate how smart technologies are transforming building safety [20].

Talaat and ZainEldin proposed a Smart Fire Detection System (SFDS) employing the YOLOv8 deep-learning algorithm, capable of rapidly identifying fires under diverse environmental conditions [21]. Leveraging IoT sensors combined with Fog and Cloud computing layers, this system demonstrated a remarkable precision rate of 97.1%, significantly surpassing traditional detection methods. The authors suggest expanding additional deep-learning architectures and broadening detection capabilities to other hazards, underscoring ongoing research needs around sensor adaptability and environmental robustness. Similarly, Xu et al. introduced a next-generation fire detection approach utilizing deep Long Short-Term Memory (LSTM) neural networks combined with Variational Autoencoders (VAE) [22]. This

advanced methodology improved fire detection sensitivity and reliability by accurately distinguishing between normal operational data and anomalies associated with fire incidents. Future research proposed by the authors emphasizes incorporating additional sensor data streams, such as smoke and CO_2 detection, demonstrating the potential for further enhancement of automated systems in complex safety-critical environments. Enhanced connectivity has also emerged as a critical element of modern fire safety systems. Alqourabah et al. presented a smart detection and automatic sprinkler system integrating IoT sensors with GSM communication technology, significantly reducing the average response time to approximately five seconds [23]. This research advocated future developments such as incorporating machine learning for predictive hazard detection and optimizing sensor placements, highlighting connectivity's critical role in rapid response coordination during emergencies. Addressing sustainability and energy efficiency, Park et al. developed a Smart Fire Safety Management System (SFSMS) capable of real-time monitoring and evacuation guidance through AI analytics and IoT sensor networks [24]. Tested in real-world scenarios, the system notably improved both evacuation efficiency and energy savings. Future research directions identified by the authors include further integration of predictive AI algorithms and expansion into comprehensive energy and safety management systems, emphasizing the pursuit of environmentally sustainable and disaster-resilient smart infrastructures.

Collectively, these highlighted studies illustrate the transformative potential of smart technologies for building safety, demonstrating significant advancements in detection accuracy, response efficiency, robust integration, and sustainable operation. Yet, these focused research efforts underscore a broader challenge: the literature remains fragmented, often emphasizing isolated system components or specific technological outputs without fully addressing holistic integration or cross-domain implications [25]. Given this fragmentation, there is a compelling need for systematic, large-scale reviews capable of synthesizing information across multiple technological domains, sensor types, and integration methods. Such comprehensive reviews would clarify which research areas are well-explored, identify knowledge gaps, and prioritize future research directions. A large-scale, holistic literature analysis as presented in this study is therefore essential to consolidate findings, inform stakeholders, and guide strategic research investments toward safer, smarter, and more resilient built environments. The PRISMA framework is widely recognized for its structured approach to conducting systematic reviews [26]. However, its application is often time-consuming and labor-intensive. Researchers must manually screen and assess each study for relevance, a process that can be both error-prone and subjective, especially when dealing with large volumes of literature [27]. This manual effort can lead to inconsistencies in study selection and data extraction, potentially impacting

the reliability of the review outcomes. Moreover, the necessity for human judgment in categorizing studies into themes or clusters introduces variability that can affect the reproducibility of the review process.

In response to the limitations of manual reviews, automated text-mining techniques and LLMs have been employed to expedite literature analysis [13], [28], [29]. While these tools can process vast amounts of data, they are not without challenges. Automated systems often struggle with accurately determining the contextual relevance of studies, leading to the inclusion of irrelevant literature or the exclusion of pertinent studies [30]. Additionally, the computational resources required to process extensive databases can be substantial, posing practical limitations for many research teams. LLMs, despite their advanced capabilities, are susceptible to generating information that appears plausible but is factually incorrect, a phenomenon known as “hallucination” [28], [30]. This issue is particularly problematic when LLMs are used to identify themes or clusters within literature, as overlapping data and thematic similarities can lead to misclassification and unreliable conclusions [31], [32]. Given these challenges, there is a growing recognition of the need for hybrid approaches that combine the strengths of manual expertise with automated tools to enhance the efficiency and accuracy of literature reviews.

Given the limitations of both traditional and automated approaches, there is a growing recognition of the need for hybrid methodologies that combine the strengths of manual expertise with automated tools. Such approaches aim to enhance the efficiency and accuracy of literature reviews, particularly in rapidly evolving fields like smart building technologies. A rapid, iterative framework allows for timely updates and adjustments, ensuring that the literature review remains current and relevant. This is especially critical in domains where technological advancements occur swiftly, necessitating agile review processes that can accommodate new information with minimal overhead.

III. METHODOLOGY

A. LITERATURE RETRIEVAL AND SCREENING

The literature retrieval process was conducted using Scopus, Web of Science (WoS), IEEE Xplore, Google Scholar, and ScienceDirect, selected for their comprehensive coverage of peer-reviewed scientific publications in the fields of engineering, technology, and safety. To identify relevant works, a structured query targeting publications related to safety dimensions in smart buildings was executed. The query included terms such as “smart building*” in combination with “fire safety”, “life safety”, “electric safety”, “evacuation”, “emergency communication”, “fire detection”, “regulation”, and “standards”, among others. The full search expression is provided in Query 1.

To prioritize contemporary contributions and ensure relevance to current technological and regulatory contexts, the search was restricted to publications from 2010 onward.

```

TITLE-ABS-KEY ("smart building*" AND "fire safety") OR
TITLE-ABS-KEY ("smart building*" AND "life safety") OR
TITLE-ABS-KEY ("smart building*" AND "electric safety") OR
TITLE-ABS-KEY (("auto* building*" OR "smart building*") AND
"scape") OR
TITLE-ABS-KEY ("smart building*" AND "fire detection") OR
TITLE-ABS-KEY ("smart building*" AND "safety") OR
TITLE-ABS-KEY ("smart building*" AND ("gas" OR "smoke")) OR
TITLE-ABS-KEY ("smart building*" AND "firefight*") OR
TITLE-ABS-KEY ("smart building*" AND "evacuation") OR
TITLE-ABS-KEY ("smart building*" AND "emergency" AND
"comm*") OR
TITLE-ABS-KEY ("smart building*" AND "literature review") OR
TITLE-ABS-KEY ("smart building*" AND "regulation") OR
TITLE-ABS-KEY ("smart building*" AND "standard*")

```

QUERY 1. Scopus search query used in this study.

This temporal filter was guided by the observed increase in both publication volume and citation activity in recent years, as illustrated in Figure 3. The filtering process yielded a total of 1,409 documents. Subsequently, these documents were distributed among members of the research team, who independently assessed each item for relevance and assigned an importance score based on methodological rigor, topical focus, and scholarly impact. Only those publications deemed pertinent and of sufficient quality were retained for further stages of the analysis.

B. LLM-ASSISTED SUMMARIZATION

The process of LLM-assisted summarization presented in this study is implemented through an original pipeline designed by the authors to efficiently and systematically extract structured information from a large volume of academic literature, while ensuring accuracy and reproducibility. The techniques integrated into this pipeline are drawn from state-of-the-art summarization research, as cited and explained in the preceding paragraphs, and were selected for their demonstrated effectiveness in enhancing informativeness, factual consistency, and structural coherence. These methods are purposefully combined, rather than applied in isolation, to maximize their applicability in a real-world use case involving high-volume, domain-specific literature reviews, ensuring both methodological rigor and operational feasibility.

Following the literature retrieval and screening stage, the selected articles undergo a preprocessing phase wherein the title, abstract, and key sections such as methodology, results, and conclusions are extracted. This step involves text cleaning procedures to remove extraneous elements, including figure captions, tables, bibliographic references, and unrelated metadata. The objective of this preprocessing is to streamline the textual input, ensuring that only the most relevant content is provided to the language model, thus optimizing the summarization performance. Once the input texts are prepared, the summarization process is conducted using advanced prompt engineering techniques, carefully tailored to balance conciseness, completeness, and thematic

coherence. In this study, we employ exclusively an Ensemble Prompting strategy [34], as prior research has demonstrated its superiority over Chain-of-Density (CoD) prompting [33] and vanilla prompting [123] in producing summaries that are both more informative and structurally consistent.

The ensemble prompt integrates multiple evidence-based components, including role-based instructions to align the model with academic summarization objectives, contextual framing to incorporate metadata such as publication year and research domain, few-shot exemplars to leverage in-context learning [124], and adversarial examples to suppress the inclusion of spurious or factually incorrect content [125]. This combination draws on findings that instruction-following improves adherence to specifications, few-shot prompting reliably enhances task performance, and adversarial testing mitigates undesired behaviors [34]. The summarization output is formatted into a structured, machine-readable schema, with predefined fields for key findings, methodological approaches, results, and limitations, enabling reproducible downstream processing such as clustering and knowledge mapping, in line with recent benchmarks on structured LLM outputs [126].

A crucial element of this methodology, complementing the ensemble prompting strategy described above, is the incorporation of a human-in-the-loop validation step. Similar hybrid frameworks, combining automated LLM-based summarization with expert review, have been shown to improve factual accuracy, reduce hallucinations, and enhance domain-specific relevance [123], [125]. In our case, domain experts systematically review each LLM-generated summary, verifying the correctness of extracted information, refining technical terminology, and correcting potential misinterpretations. This iterative feedback loop serves not only to improve the immediate quality of the summaries but also to incrementally optimize the ensemble prompt templates, consistent with adaptive prompt refinement practices reported in recent LLM evaluation studies [34], [127]. To address scalability, we adopt a recursive MapReduce strategy, a hierarchical processing approach also employed in large-scale text summarization pipelines [34], which mitigates token-length constraints by processing documents in manageable chunks and consolidating intermediate results into coherent final summaries. This design ensures robustness, adaptability, and reproducibility across large and dynamically growing corpora, while aligning with best practices in LLM-assisted literature review workflows.

While LLM-generated summaries can accelerate the literature review process, they can also introduce biases or inaccuracies due to model limitations. In this study, all LLM outputs were validated through expert review, with original sources cross-checked to confirm factual accuracy and contextual integrity. This human-in-the-loop approach aligns with recent recommendations for combining AI-based text generation with domain expert oversight to ensure reliability in research synthesis [35], [36], [37].

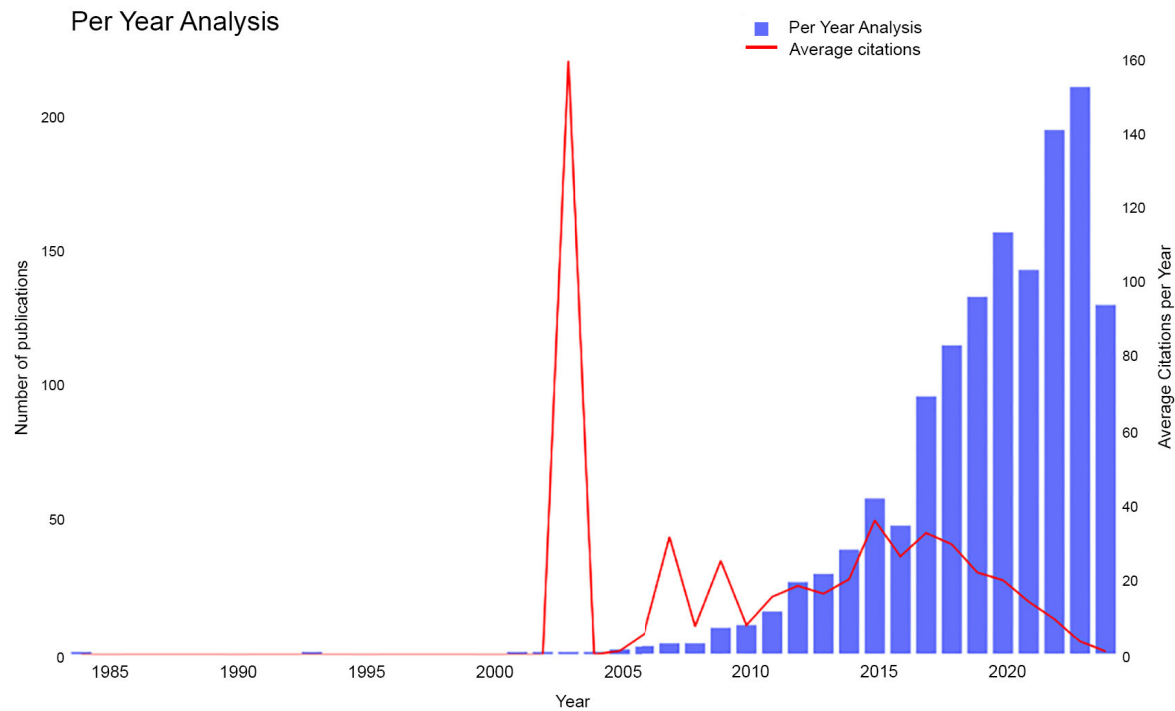


FIGURE 3. Number of documents (blue bars) and average citations (red line) per year. The pick in citations is due to a single book in 2003.

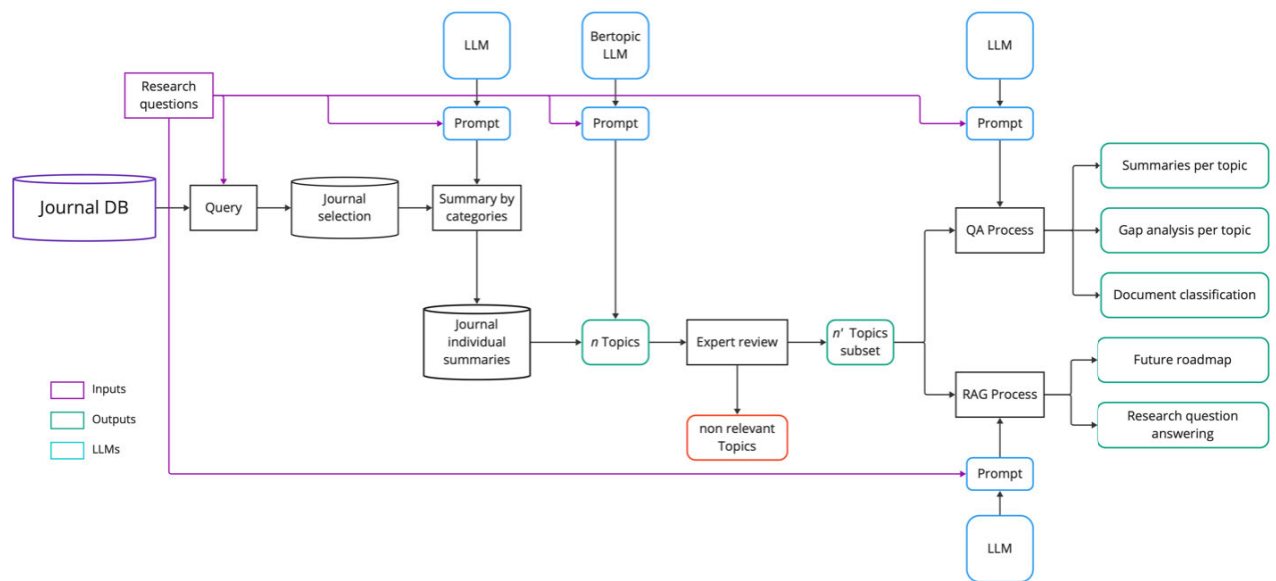


FIGURE 4. Summarization methodology schema.

The summarization methodology described above is operationalized through the multi-stage pipeline illustrated in Fig. 4. This process follows the approach proposed in [34] and [38], integrating Large Language Models (LLMs), prompt engineering, and expert validation to enable large-scale document synthesis. The workflow begins with a

structured query across journal databases to retrieve a corpus of relevant literature, which is then filtered through a human-guided journal selection step. Each journal is individually summarized using LLMs guided by structured prompts. These initial summaries are categorized and subsequently processed using BERTopic for topic modeling [39],

a machine learning technique that automatically groups related documents by identifying patterns in their content and assigning them to coherent topics. The resulting topic clusters undergo a refinement phase, where expert reviewers evaluate and adjust the topic set, producing a validated subset of salient themes. For each topic, LLM-based prompts generate comprehensive summaries and support a question-answering (QA) process that facilitates targeted information extraction. This phase culminates in per-topic gap analyses and document classifications, which are then synthesized into a roadmap for future research. The final stage involves answering predefined research questions via a Retrieval-Augmented Generation (RAG) strategy [41], a method that first retrieves the most relevant information from the document collection and then uses a large language model to generate a synthesized, context-aware answer. This approach leverages LLMs to integrate content across the corpus. This iterative pipeline not only enables scalable and systematic literature analysis but also reflects the layered summarization framework and prompt design strategies detailed in the original reference study.

C. TOPIC CLUSTERING AND KNOWLEDGE MAP CREATION

To group the articles into major thematic categories, a hybrid topic modeling pipeline was applied, combining transformer-based document embeddings with unsupervised clustering and LLM-based topic refinement. The process begins with the generation of high-dimensional sentence embeddings using a dense embedding model optimized for semantic similarity tasks. These embeddings are projected into a lower-dimensional space using Uniform Manifold Approximation and Projection (UMAP) [128], which was selected for its ability to reduce complexity. This dimensionality reduction facilitates the detection and visualization of meaningful patterns. Clustering is then performed with Hierarchical Density-Based Spatial Clustering of Applications with Noise (HDBSCAN) [129], selected because it can automatically find topic groups of different sizes and shapes without requiring a predefined number of clusters, while also identifying and excluding noisy or irrelevant points. Figure 5 presents a two-dimensional UMAP visualization of the clustered documents. Each color corresponds to a distinct topic cluster, while each dot represents an individual document within the corpus. The spatial distribution in the plot reflects the pairwise distances among high-dimensional vector representations of the documents, projected onto two dimensions for interpretability. In this representation, proximity between dots indicates semantic similarity, allowing for a visual assessment of topical coherence and separation across clusters.

To enhance interpretability, class-based Term Frequency-Inverse Document Frequency (TF-IDF, specifically c-TF-IDF) was employed to extract representative keywords for each topic, and large language models, prompted with few-shot and Chain of Density techniques, were used to assign

descriptive names to the resulting clusters. This iterative process, supported by expert review, ensures that the final set of topics reflects coherent, domain-relevant themes, which serve as the basis for knowledge map construction.

D. EXPERT REVIEW AND VALIDATION OF THEMATIC CLASSIFICATION

In this study, the consistency of thematic labels assigned to literature clusters was evaluated through a structured review process involving a multidisciplinary panel of five independent experts, including specialists in construction, electronics, computer science, and fire safety. Each expert classified the relevance of selected articles into three categories (high, medium, or low) based on their assessment of the clarity and conceptual meaningfulness of the topic associations within the domain of smart building safety. The evaluated clusters are considered *boundary objects* in the sense described by Star and Griesemer [130], meaning that they are inherently open to differing interpretations depending on the disciplinary perspective. To quantitatively measure the level of consensus among the raters, Fleiss' Kappa (κ) was applied. This statistical measure is specifically designed to assess the reliability of agreement among multiple raters assigning categorical ratings to items and is defined as follows:

$$\kappa = \frac{\bar{P} - \bar{P}_e}{1 - \bar{P}_e}$$

where $\bar{P}$ is the observed agreement proportion and $\bar{P}_e$ is the expected agreement by chance. To collect expert input, a structured form was developed that presented each AI-generated Custom Name as a descriptive title summarizing the main theme of a topic cluster, as derived from a Large Language Model. Each name was evaluated by the raters along two axes: *Meaningfulness* and *Importance*. *Meaningfulness* asked experts whether the Custom Name coherently and logically captured a relevant research concept, regardless of alignment with the project's goals. *Importance* asked them to judge the Custom Name's significance relative to the project's specific research objectives. Ratings for both dimensions followed a three-point Likert scale (High, Medium, Low). This dual-assessment strategy allowed the distinction between the conceptual clarity of a topic and its strategic relevance to the study. Given the interdisciplinary nature of the panel and the interpretive flexibility of boundary objects, very high inter-rater agreement is not expected; however, obtaining positive and non-trivial κ values remains a meaningful indicator of a shared underlying understanding across disciplines. The inter-rater agreement analysis yielded a Fleiss' Kappa of 0.34 for *Meaningfulness* and 0.25 for *Importance*, indicating a fair level of agreement in both dimensions. These results suggest that while some variation in interpretation exists, there is a meaningful level of expert consensus that supports the reliability of the thematic labels and their alignment with project objectives.

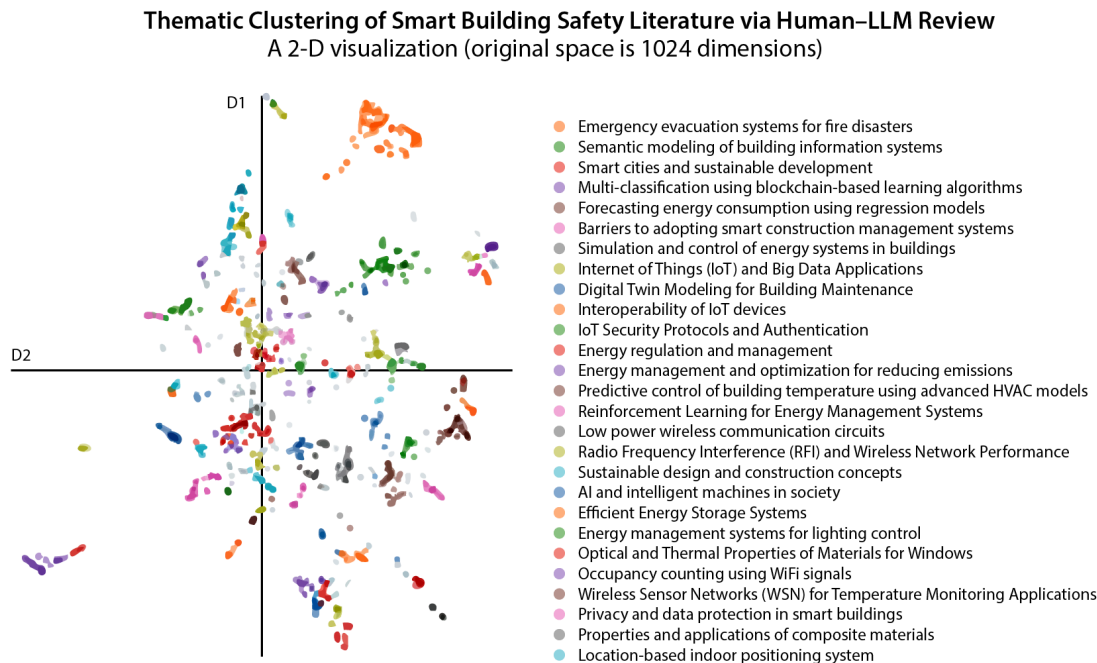


FIGURE 5. Topic representation in two dimensions of topic clusters using UMAP. Each point represents a paper, colored by cluster. UMAP preserves semantic structure, highlighting coherence and separation among topics.

E. GAP ANALYSIS

To identify research gaps across thematic clusters, a multi-step analytical strategy was implemented, combining structured summarization and LLM-based inference. The analysis utilized a state-of-the-art version of OpenAI available at the time of the experiments: “gpt-4-turbo-2024-04-0”. For each topic cluster resulting from the BERTopic pipeline, detailed per-document summaries were generated using a custom prompt framework. These summaries expanded significantly on the abstracts by extracting targeted metadata fields, such as key technologies, methodologies, future research directions, sensor types, communication protocols, and relevance to the predefined research questions. This enriched dataset served as input for a secondary analysis using a specialized LLM prompt explicitly designed to identify both explicit and latent research gaps. The prompt instructed the model to extract gaps explicitly mentioned by the original authors and to conduct a broader analysis to uncover underexplored areas based on the state of the field. The model returned structured outputs containing a concise paragraph of gap analysis per document, organized as a Python dictionary for downstream processing. This initial output was then reviewed and refined through iterative discussions among domain experts, who validated the relevance and quality of the identified gaps and contributed additional insights where necessary. This process ensured that the final set of research gaps reflected both the internal content of the literature and an expert-informed synthesis of broader disciplinary challenges, thereby enabling a robust and transparent gap analysis across the corpus.

The structure and design of the gap analysis prompt, presented in Fig. 6, incorporate a series of advanced prompting strategies to ensure analytical rigor, factual accuracy, and reproducibility. The prompt is explicitly structured into four sequential steps that guide the language model through a two-tiered evaluation process. The first tier requires the extraction of research gaps explicitly mentioned within the provided summaries of the clustered papers, ensuring that conclusions are grounded strictly in the input data. The second tier extends the analysis by leveraging the language model’s broader domain knowledge to identify additional, implicit research gaps that may not have been articulated by the original authors. To guarantee consistency and facilitate downstream processing, the prompt mandates a standardized output format using nested Python dictionaries, linking each paper to its title, year, and the two distinct gap analyses. This design integrates role-based prompting, step-by-step task decomposition, and scope control to reduce hallucination and promote traceable reasoning across a diverse set of document summaries. An example of the structured output generated through this process is provided in Fig. 7.

F. FUTURE ROADMAP ANALYSIS

To generate the roadmap of future research and development initiatives presented in IV-D, a structured prompting strategy tailored to each thematic cluster is employed. The prompt, detailed in Fig. 8, instructs the language model to analyze concatenated summaries of papers within each class and derive actionable, field-relevant initiatives. This process

```

prompt_template = """
You are tasked with analyzing research gaps based on the summaries of
academic papers provided. For each paper, follow these steps:

1. Carefully read the provided summary of the paper.
2. Identify and extract research gaps explicitly mentioned by the
   authors or implied by the paper's content. Focus solely on gaps
   described in the summary, and do not infer or fabricate gaps beyond what
   is provided.
3. Based on the summary and using your own knowledge as an advanced
   language model, perform a broader analysis to identify additional
   potential research gaps that the authors may not have explicitly
   mentioned. This analysis should be informed by current trends and
   challenges in the paper's field.
4. Write a detailed yet concise paragraph for each paper summarizing
   both the explicit research gaps identified in the summary and the
   broader analysis from step 3. Use an academic tone that avoids overly
   complex or verbose language.

**Instructions for Response Formatting:**
Return your response as a Python dictionary where each key corresponds
to the paper's 'Id', and the value is another dictionary containing the
following keys:
- 'Title': The title of the paper.
- 'Year': The publication year of the paper.
- 'Gap_analysis': A concise paragraph summarizing the explicit research
  gaps identified based on the summary.
- 'Model_analysis': A concise paragraph summarizing the additional
  research gaps identified through the broader analysis.

Example output:
{1: {
  "Title": "Advances in IoT Sensor Networks",
  "Year": 2022,
  "Gap_analysis": "The authors identify the need for improved
  scalability in IoT sensor networks and highlight the lack of
  adaptive algorithms for heterogeneous environments.",
  "Model_analysis": "Based on the current state of IoT research,
  additional gaps include the lack of robust security frameworks for
  sensor data and the integration of low-power communication
  protocols for large-scale deployments."
}},
2: {
  "Title": "AI Applications in Healthcare",
  "Year": 2021,
  "Gap_analysis": "The paper points to a lack of integration between
  AI systems and existing healthcare infrastructure, emphasizing the
  need for data standardization.",
  "Model_analysis": "Further analysis suggests gaps in the
  development of explainable AI models to increase trust among
  healthcare professionals and patients, as well as the need for
  addressing bias in training datasets."
}
}

Apply this process for paper: '{paper}' with summary: '{summary}'.
Analyze each paper and provide your findings in the specified format.
Return the dictionary and nothing else.
"""

```

FIGURE 6. Prompt template used for Gap Analysis.

```

{1: {
  'Gap_analysis':
  'The paper explicitly mentions future research goals to develop more
  accurate data prediction techniques and advanced smart technologies
  to promote carbon neutrality by 2030. This indicates a research gap
  in the current accuracy of data prediction and the sophistication of
  smart technologies in the context of fire safety and energy
  management systems.',
  'Model_analysis':
  'While the paper outlines advancements in AI-based fire safety and
  energy management, additional research gaps can be inferred in
  several areas. First, the integration of these systems into existing
  building infrastructures could be explored further, particularly in
  older or historically significant buildings where retrofitting modern
  technologies poses unique challenges. Second, the user experience and
  usability of the AR-based mobile/web application for evacuation could
  be studied more deeply to ensure effectiveness across diverse
  populations, including those with disabilities. Lastly, the
  resilience and security of the IoT and cloud components against cyber
  threats remain critical, especially given the sensitivity and
  importance of fire safety systems.'
  'Title':
  'Smart Fire Safety Management System (SFSMS) Connected with Energy
  Management for Sustainable Service in Smart Building Infrastructures',
  'Year': 2023)
}

```

FIGURE 7. Gap Analysis output.

combines two layers of inference: first, it extracts future directions directly suggested or implied in the literature;

second, it proposes additional initiatives informed by the model's broader domain knowledge and aligned with current technological trends. The prompt explicitly guides the generation of initiatives related to AI-driven early detection, predictive event prevention, intelligent evacuation planning, and advanced information systems for first responders. Each response is formatted as a Python dictionary, mapping each class to a single, cohesive list of clearly worded initiatives that begin with action verbs and specify intended deliverables or performance targets. This approach ensures uniformity, clarity, and relevance across all roadmap outputs.

```

prompt_template_list = """
You are tasked with creating a **Future Research and Development
Initiatives List** based on grouped summaries of academic papers. For
each class, follow these steps:
1. Carefully read the provided summaries of the papers in the class.
   Each summary has been concatenated into a single string for the
   respective class.
2. Based on the summaries, identify and describe specific initiatives
   for future research and development that align with the challenges and
   gaps highlighted. Ensure that the initiatives are concrete, actionable,
   and directly relevant to the field.
3. Additionally, using your broader knowledge as an advanced language
   model, propose further initiatives informed by current advancements and
   trends in the field. This analysis should include:
   - Early detection systems using AI.
   - Prevention of events (e.g., fire, smoke, electrical problems) and
     their correlated triggers (e.g., sprinklers, HVAC, vent activation)
     through improved methods (e.g., ML, AI).
   - Intelligent, segmented, and personalized evacuation plans.
   - Advanced systems for intelligent information, alerts, and alarms for
     first responders (e.g., AI-driven contextual maps, heat maps).
   - Other emerging technologies or methodologies relevant to the class
     topic.
4. For each class, return a **single list** of initiatives formatted as
   follows:
   - Use action verbs in the infinitive form to start each item (e.g.,
     "Develop," "Implement," "Explore").
   - Clearly define the deliverables of the initiative (e.g., technology,
     system, framework, or method).
   - Optionally include general acceptance metrics or goals (e.g.,
     "achieving 95% accuracy", "ensuring compatibility across platforms").

**Instructions for Response Formatting:**
- Return your response as a **Python dictionary**.
- Each key corresponds to the class_name.
- Each value is a **list of strings**, where each string is a specific
  initiative formatted as described above.

**Example output:**
{
  "Class 1": [
    "1. Develop scalable IoT frameworks for adaptive solutions in
    diverse operational settings.",
    "2. Implement energy-efficient communication protocols for
    IoT systems to reduce power consumption by 20%.",
    "3. Explore privacy frameworks for IoT implementations,
    ensuring compliance with GDPR standards."
  ],
  "Class 2": [
    "1. Integrate AI tools with healthcare infrastructure to
    improve diagnosis accuracy to over 90%.",
    "2. Design standardized datasets for healthcare applications
    to ensure model generalization.",
    "3. Develop explainable AI technologies to enhance trust
    among healthcare professionals."
  ]
}

**Important Notes:**
- Ensure that each class produces a **single list of actionable
  initiatives** as described above.
- Avoid splitting the output into multiple sections or paragraphs;
  provide a cohesive and concise list for each class.
Input:
- '{class_name}': The name of the class you are analyzing.
- '{summaries}': A concatenated string containing summaries of papers
  for that class.
Return the Python dictionary directly and nothing else.
"""

```

FIGURE 8. Prompt template used for future directions analysis.

G. ITERATION AND SCALABILITY

The proposed methodology is designed to be both scalable and adaptable, supporting growth in two ways. Vertically,

the pipeline can handle thousands of documents efficiently through modular steps such as batch processing, dimensionality reduction, and multi-stage summarization, which help manage the computational limits of large language models. Horizontally, the framework is independent of any specific query or research domain, making it easy to adjust for different topics, disciplines, or application areas by changing search settings and prompt templates. This flexibility allows the entire process to be repeated with updated datasets, making it well-suited for fast-changing fields where new publications and emerging trends continually reshape the research landscape.

IV. RESULTS AND FINDINGS

A. OVERALL LITERATURE LANDSCAPE

The review synthesizes 83 high-quality publications drawn from an initial pool of 1,409 documents retrieved via Scopus, filtered from 2010 onward to ensure contemporary relevance. These articles span various facets of smart building safety and are selected through expert screening based on methodological rigor and relevance. The temporal distribution of publications and citation activity is shown in Fig. 3, reflecting the field's growth and increasing academic interest. The final corpus includes research covering fire, electrical, and life safety, with common keywords pointing to trends in AI, IoT, automation, and sensing technologies.

B. IDENTIFIED THEMES AND CLUSTERS

Thematic analysis reveals nine key clusters, which are the outcome of the Topic Clustering, Expert Review, and Knowledge Map Creation step previously documented in this paper. These clusters structure the reviewed literature into coherent research areas: Advanced Sensing Technologies, Automation and Smart Systems, Enhanced Connectivity and Integration, Standard Compliance Management, Cybersecurity, Specialized Applications, Sustainability and Energy Efficiency, Digital Twin, and Decision-Making in Smart Disaster Response Systems. Each cluster captures distinct technological and methodological trends within smart building safety research.

- **Advanced Sensing Technologies:** Focuses on innovations such as AI-powered detection, adaptive algorithms, dynamic thresholding, and hybrid sensing devices designed to improve fire detection accuracy, environmental adaptability, and false alarm reduction.
- **Automation and Smart Systems:** Covers AI-driven predictive maintenance, autonomous suppression systems, IoT-enabled remote monitoring, and biometric-based evacuation aids, enhancing both prevention and emergency response.
- **Enhanced Connectivity and Integration:** Encompasses the integration of fire safety systems with broader smart building infrastructures, cloud-based environmental monitoring, and IoT-based communication networks for real-time data sharing and system coordination.

- **Standard Compliance Management:** Addresses research efforts aimed at improving fire safety systems' compliance with regulatory standards, particularly in sensor sensitivity, suppression system performance, and false alarm mitigation.
- **Cybersecurity:** Examines vulnerabilities in IoT-connected safety systems, including risks of unauthorized access, system sabotage, and the need for AI-based anomaly detection to safeguard critical fire and life safety infrastructure.
- **Specialized Applications:** Focuses on tailored safety solutions for unique environments, such as industrial facilities, wearable technologies for emergency response, and resilient system designs for extreme or specialized conditions.
- **Sustainability and Energy Efficiency:** Investigates environmentally responsible designs in fire safety technology, such as energy-efficient sensors, recyclable materials, and battery-less wireless systems.
- **Digital Twin:** Explores the use of virtual replicas of buildings, integrating real-time sensor data and BIM modeling, to enhance fire safety planning, system management, emergency visualization, and training via augmented reality.
- **Decision-Making in Smart Disaster Response Systems:** Concentrates on systems that enable real-time threat assessment, coordinated evacuation, and first responder support through the integration of IoT, AI, and real-time analytics.

Table 1, provides a structured categorization of the literature review papers analyzed in this study.

C. GAP ANALYSIS

The gap analysis is conducted by leveraging the thematic clusters previously identified through the Topic Clustering and Knowledge Map Creation process. Each cluster, corresponding to a specific research category, aggregates a set of documents as detailed in Table 1. To systematically extract both explicit and inferred research gaps, the structured prompt methodology outlined in Table 1 is applied. This approach enables the generation of consistent, detailed analyses across all categories by first identifying gaps mentioned within the literature itself (extracted) and subsequently supplementing these with broader insights derived from the language model's domain knowledge (extended). The results of the extracted and extended gap analyses are presented in Tables 2 and 3, respectively.

Together, the extracted and extended gap analyses offer a comprehensive view of the current limitations and future needs across the landscape of smart building safety research. Well-documented gaps include the lack of real-world validation for AI-based fire detection systems, limited interoperability among IoT-enabled devices, and the absence of standardized protocols for integrating smart systems with traditional fire alarm control panels. These are frequently cited concerns across multiple studies. Less visible but

TABLE 1. Classification of literature review papers by category and sub-categories (see cited references in references).

Category	Paper #	Sub-categories
Advanced Sensing Technologies	[40]	Adaptive Algorithms and Dynamic Thresholding
	[40], [41], [42], [43], [21], [44], [45], [46], [47], [48], [49], [50], [51], [52], [111]	AI-Powered Detection and Predictive Sensors
	[42], [44], [48], [49], [53], [54]	Customization in Detection and Multi-Environment Adaptability
	[41], [55]	Enhanced Sensor Durability and Environmental Adaptability
	[40], [45], [53], [54], [55]	Multi-Spectrum, Gas Sensors, Optical Sensors and Hybrid Sensing Devices
	[45], [50], [56]	Camera Object Detection Model
Automation and Smart Systems	[57], [59], [22], [60], [61], [62], [63], [64], [65], [66], [24], [67], [68], [69], [70], [71], [72], [73], [74], [75], [76], [77], [78], [79], [58]	AI-Driven Predictive Maintenance and Self-Monitoring Capability
	[24], [40], [41], [42], [44], [45], [46], [50], [57], [59], [22], [65], [66], [73], [74], [76], [77], [78], [80], [81], [82], [84], [86], [88], [90], [91], [92], [23], [93], [94], [95], [96], [97], [98], [99], [100], [101], [102]	Autonomous Fire Prevention and Remote Monitoring Systems (including first response system)
	[47], [56], [59], [63], [65], [66], [67], [69], [79], [86], [103]	Integration with Smart Grids and IoT-Based Automation
	[62]	Smart and Connected Devices with Biometric Integration
	[55], [66], [103]	Smart and Connected Devices for Emergency Evacuation
	[61]	Synthetic Data Generation and Advanced Data Augmentation
	[19], [43], [48], [51], [52], [55], [58], [57], [65], [67], [69], [70], [71], [74], [75], [79], [80], [82], [84], [85], [86], [87], [88], [89], [90], [23], [93], [95], [96], [97], [99], [100], [101], [102], [103], [104], [105], [106], [107], [108], [109], [110], [111], [112]	Wireless Sensors and Communication Solutions
	[52], [53], [22], [67], [74], [77], [78], [80], [81], [84], [89], [93], [105], [107], [108], [110], [114]	Integrated Cybersecurity for Electrical and Fire Safety Systems
	[68], [71], [72], [76], [78], [90], [93], [94], [95], [96], [97], [98], [100], [102], [103], [110], [111], [114], [116]	Decision Making in Smart Disaster Response System
Digital Twin	[46], [56], [66], [68], [73], [83], [91], [92], [96], [116]	Building Information Modeling
	[24], [68], [94]	Augmented Reality
Enhanced Connectivity and Integration	[19], [43], [54], [55], [60], [63], [64], [70], [75], [87], [99], [103], [104], [106], [112], [113]	Smart Building Integration and Connectivity with Smart Grids
	[21], [47], [48], [54], [64], [70], [72], [75], [86], [87], [90], [91], [99], [101], [102], [106], [108], [110], [114]	Environmental Monitoring with Cloud-Based Data Sharing
	[19], [51], [56], [60], [81], [89], [23], [101], [103], [104], [107], [108], [109], [112], [113], [114], [24]	IoT-Connected Systems and Wireless Networking
	[52], [61], [95]	Modular, Customizable, and Scalable Industrial Systems
Specialized Applications	[103], [115]	Portable, Wearable, and Plug-and-Play Detection Devices
	[40]	Durable and Interactive Smoke Detectors with Voice Activation
Standard Compliance Management	[72], [73], [83], [84], [88], [98], [103], [105]	Regulatory Compliance and Safety Standards
Sustainability and Energy Efficiency	[19], [24], [47], [49], [51], [53], [95], [62], [63], [64], [79], [92], [104], [109], [112], [113]	Energy-Efficient Sensors and Battery-Less Power Systems
	[92]	Recyclable Materials and Green Technology Designs

critical gaps emerged through extended analysis, such as the need to improve accessibility and user experience for cognitively declined individuals in smart environments, the absence of dynamic hazard modeling integrated with 3D building data, and the underexplored potential of augmented reality for emergency responder training. Additionally, methodological limitations persist in the scalability of digital twin systems, the economic feasibility of deploying advanced sensor technologies in older infrastructures, and the lack of sociotechnical frameworks to align technological

advancement with regulatory and behavioral dimensions. These insights not only reinforce the urgency of addressing known deficiencies but also emphasize the importance of expanding research beyond conventional boundaries. The findings serve as a foundation for a focused and actionable research roadmap presented in the following section.

D. POTENTIAL FUTURE DIRECTIONS

Building on the thematic clusters and the gap analysis presented in the previous sections, this subsection outlines a

TABLE 2. Extracted gap analysis from the corpus of documents.

Category	Extracted Gap Analysis
Advanced Sensing Technologies	The summaries indicate several research gaps in the field of advanced sensing technologies for fire detection and smart building applications. These include the need for practical hardware implementations of neural network-based fire detection systems, real-time enhancements for camera-based systems, integration of environmental parameters like humidity and light into predictive models, cost reduction in sensor technologies, and the development of advanced algorithms for data interpretation. Additionally, there is a call for on-site validation of digital twin frameworks and the extension of these systems to other emergency scenarios.
Automation and Smart Systems	The summaries reveal several research gaps in the field of automation and smart systems. One significant gap is the need for more comprehensive and adaptable cyber-physical systems that can fully support the autonomy and independence of occupants, particularly those with cognitive declines. There is also a gap in the development of more effective fire safety systems that integrate real-time data and machine learning to predict and respond to fire incidents more accurately. Additionally, the studies highlight the need for improved usability and acceptability of these technologies, addressing ethical concerns, and enhancing the robustness of systems against failures.
Cybersecurity	The summaries explicitly mention several research gaps such as the need for refining information systems in smart buildings, enhancing privacy controls, developing more advanced sensor technologies, and improving the scalability and effectiveness of IoT-based fire detection systems. There is also a focus on enhancing the security and privacy of smart city applications, and the integration of data provenance in PLC systems to detect safety and security violations.
Decision Making in Smart Disaster Response System	The summaries highlight several explicit research gaps in smart disaster response systems. These include the need for unified protocols for seamless integration and interoperability of home automation systems, the necessity to handle ambiguity and uncertainty in the evaluation of smart disaster response systems, and the challenges in adopting Digital Twins technology for fire safety management due to technical, economic, and stakeholder-related barriers.
Digital Twin	The summaries highlight several research gaps including the need for more comprehensive coverage of multi-story buildings, enhancing computational efficiency, integrating additional data sources like advanced environmental sensors, and incorporating machine learning for predicting fire spread patterns. There is also a call for expanding augmented reality training to include more complex scenarios and diverse user groups, developing economically viable solutions for digital twin adoption, and improving real-time dynamic hazard models integration with 3D building models.
Enhanced Connectivity and Integration	Explicit research gaps identified from the summaries include the need for further deployment of IoT systems across different building types and locations, cost-effectiveness evaluations, real-world performance testing of proposed systems, and scalability testing in diverse environments. There is also a call for more advanced control algorithms, integration of IoT with machine learning for enhanced functionalities, and the development of unified protocols for better integration and interoperability of home automation systems.
Specialized Applications	The summaries reveal several explicit research gaps across different specialized applications. In construction, there is a need for further exploration of AI's role in modular construction to enhance safety and efficiency. In fire safety, the optimization of fire detection systems and the integration of advanced computational models are highlighted. For cyber-physical systems in smart buildings, gaps include the lack of comprehensive applications supporting autonomy, usability issues, and ethical concerns. Home automation systems lack unified protocols for integration and interoperability. The Vital Responder project identifies the need for real-world deployment and expanded functionalities for emergency response systems. Lastly, the ontology for firefighters needs further alignment with other emergency management systems and validation in diverse scenarios.
Standard Compliance Management	The papers collectively identify several research gaps, including the need for sociotechnical approaches in different regulatory environments, advanced tools for risk and systems analysis that incorporate social behaviors, hardware system architecture enhancements in fire alarm control panels, and the development of unified protocols for home automation systems. Additionally, there is a call for more granular sensor data integration in fault detection systems and the extension of AI models to handle complex building structures for fire safety.
Sustainability and Energy Efficiency	Explicit research gaps identified include the need for deploying IoT systems across various building types and evaluating their cost-effectiveness, enhancing the color range and reducing dependency on external stimuli in thermochromic materials, and developing more advanced sensor technologies and machine learning models for smart buildings. There is also a call for integrating additional smart technologies and improving the interoperability between different systems to enhance building safety and operational efficiency.

structured roadmap of targeted research directions aimed at advancing fire, electrical, and life safety within smart building environments. Each proposed action is grounded in the insights derived from both the literature review and expert-guided gap identification and is directly linked to one or more thematic categories identified earlier. The recommendations span technical innovations, such as AI-driven evacuation systems, blockchain-enhanced cybersecurity frameworks, and deep learning-based fire detection models, as well as integrative solutions like unified IoT protocols, augmented reality applications for emergency response, and sociotechnical approaches to standard compliance. Table 4 in Appendix A, presents these future directions, offering a practical blueprint to guide interdisciplinary research and system development efforts across the smart building ecosystem.

Collectively, the proposed future directions respond to both well-established and emerging research gaps, providing a comprehensive vision for the evolution of safety-critical smart building technologies. For instance, the integration of digital twins with machine learning to predict fire spread patterns addresses documented limitations in real-time hazard

modeling, while the call for personalized evacuation plans using dynamic AI algorithms reflects newer challenges tied to occupant variability and environmental complexity. Equally, the expansion of fault-tolerant communication protocols and the adoption of semantic frameworks for firefighter decision-making tackle interoperability and data accessibility, two cross-cutting issues that affect multiple domains. These targeted actions not only align with current technological trajectories but also anticipate the growing demands for resilience, adaptability, and ethical design in future smart infrastructure systems.

V. DISCUSSION

A. IMPLICATIONS FOR RESEARCH AND PRACTICE

The thematic clusters, expert summaries, and gap analysis presented in this study offer initial guidance for researchers, practitioners, and policymakers working at the intersection of smart building technologies and life safety. Academically, the identified gaps, such as the limited real-world validation of AI-based fire detection systems or the need for standard protocols in IoT integration, highlight high-impact areas

TABLE 3. Extended gap analysis from the corpus of documents.

Category	Extended Gap Analysis
Advanced Sensing Technologies	Beyond the explicitly mentioned gaps, potential research areas could focus on the scalability of these technologies to different types of buildings and environments, enhancing the robustness of AI models under varying conditions of fire severity, and improving the integration of IoT technologies for real-time monitoring and control. There is also a significant opportunity to explore the use of machine learning for predictive maintenance and anomaly detection in building management systems. Furthermore, the development of low-cost, high-efficiency sensors that can be easily integrated into existing building infrastructures could revolutionize the market, particularly for retrofitting older buildings with smart technologies.
Automation and Smart Systems	Additional potential research gaps include the need for standardization in IoT implementations to ensure compatibility and security across different systems and devices. There is growing demand for integrating advanced predictive analytics and AI to enhance decision-making in emergencies. Furthermore, as buildings become more connected, addressing privacy and data security comprehensively is critical. Lastly, integrating renewable energy sources and sustainability practices into smart building designs represents a significant area for future research to reduce environmental impact.
Cybersecurity	Additional potential research gaps include the need for developing comprehensive frameworks that address both cybersecurity and physical safety in smart environments. This could involve creating more robust, adaptive cybersecurity measures that can anticipate and mitigate emerging threats in real-time. There is also a significant opportunity to explore the integration of blockchain technology for secure, decentralized data management across smart systems. Furthermore, the development of standards and protocols specifically tailored for IoT implementations in safety-critical systems like fire alarm control panels could enhance interoperability and security. Lastly, the application of AI and machine learning could be expanded to predict and respond to cybersecurity threats dynamically, thereby improving the resilience of smart infrastructure against cyber-attacks.
Decision Making in Smart Disaster Response System	Additional potential research gaps in smart disaster response systems could include the development of more advanced predictive models using AI to anticipate disaster scenarios and optimize response strategies. There is also a need for comprehensive frameworks that integrate various technologies such as IoT, AI, and Digital Twins to enhance real-time decision-making and operational efficiency during disasters. Furthermore, addressing cybersecurity concerns in IoT-enabled disaster response systems is crucial to protect sensitive data and ensure the reliability of these systems in emergency situations.
Digital Twin	From a broader perspective, additional potential research gaps include the need for standardization in digital twin technologies to ensure compatibility and interoperability across different systems and platforms. There is also a significant gap in the validation of these technologies in real-world settings, which is crucial for their practical deployment. Furthermore, the integration of real-time data analytics and more advanced AI algorithms could enhance the predictive capabilities of these systems, thereby improving emergency response outcomes. Lastly, addressing privacy and security concerns related to the extensive data used in digital twin systems could also be a vital area of future research.
Enhanced Connectivity and Integration	Broader gaps include enhanced data security as IoT devices proliferate, standards and regulations for IoT integration in building management systems, integration of renewables with IoT for sustainable smart buildings, and robust fault detection and diagnostics for long-term reliability.
Specialized Applications	The broader analysis suggests additional research gaps that could significantly impact the effectiveness and adoption of specialized applications. For AI in construction, integrating real-time data analytics and predictive maintenance could further enhance project outcomes. In fire safety, developing adaptive algorithms that can dynamically adjust to changing environmental conditions could improve detection accuracy and response times. For cyber-physical systems, there is a critical need for more robust data privacy frameworks to protect sensitive information in smart environments. Home automation could benefit from the development of more intuitive user interfaces and integration with smart city infrastructures. For emergency response technologies, enhancing data transmission reliability in adverse conditions is crucial. Finally, the ontology for firefighters could be expanded to include real-time updates and AI-driven predictions to better support decision-making during emergencies.
Standard Compliance Management	Additional potential research gaps include the need for comprehensive frameworks that integrate emerging technologies such as AI and IoT with traditional building management systems to improve interoperability, security, and user engagement. There is also a significant gap in developing predictive maintenance models that can anticipate failures and optimize system performance. Furthermore, the integration of real-time data analytics and machine learning could provide more dynamic and adaptive safety and compliance measures, which are crucial for handling the increasing complexity and requirements of modern building infrastructures.
Sustainability and Energy Efficiency	From a broader perspective, additional potential research gaps include the need for developing more robust and scalable IoT frameworks that can seamlessly integrate with existing building infrastructures. There is a significant opportunity to explore the use of renewable energy sources within smart building systems to further enhance sustainability. Moreover, addressing data security and privacy concerns in IoT implementations is crucial, as is the development of more sophisticated data analytics tools to process and utilize the vast amounts of data generated by smart building systems. Finally, enhancing user interfaces and experience in managing and interacting with smart building systems could also be a valuable area of research, ensuring that these technologies are accessible and beneficial to a broader range of users..

for future empirical studies, theoretical advancements, and interdisciplinary collaborations. For industry stakeholders, this roadmap offers actionable intelligence for technology development, particularly in areas such as digital twin deployment, advanced sensing, and intelligent evacuation systems. Policymakers may find value in the study’s emphasis on compliance, standardization, and ethical integration of emerging technologies into existing infrastructure and regulations.

Based on a comprehensive literature review and a workshop hosted by the Fire Protection Research Foundation (FPRF) in January 2025, the following case studies were identified. The workshop brought together industry professionals, first responders, researchers, and other stakeholders to explore how smart and connected systems impact fire,

electrical and life safety in buildings. One example is the CareDEX project, led by Professor Nalini Venkatasubramanian at the University of California, Irvine [118]. Funded by DARPA’s Brandeis Program and built on the award-winning TIPPERS platform, CareDEX enables secure, real-time data exchange between emergency responders and healthcare providers. It supports real-time location tracking, evacuation monitoring, medical surge planning, and infrastructure status updates. Successfully tested in large-scale exercises like the Great California Shakeout, CareDEX demonstrates how IoT-driven insights can enhance disaster preparedness for aging populations. Another study proposes a real-time evacuation model that integrates an enhanced Cellular Automata (CA) method with IoT sensors, AI cameras, and dynamic signage. This system allows multi-directional movement, uses

Potential Energy Fields (PEF) to guide evacuees, and adapts routes based on live sensor data. Tested at Beijing Capital Airport Hospital, it reduced evacuation time by up to 72%. Key components include fire and crowd-detecting sensors, AI-powered behavior monitoring, edge computing with LoRa networks, and real-time signage updates, offering a smarter, faster, and more adaptive evacuation solution [119]. A third case study introduces the Smart Fire Safety Management System (SFSMS), an AI-powered platform designed to enhance fire safety, energy efficiency, and sustainability in smart cities [24]. The SFSMS incorporates several integrated capabilities, including

- AI-based fire detection using deep learning.
- AR-guided evacuation with real-time route updates.
- IoT sensors for fire and occupancy monitoring.
- A Virtual Edge Gateway (VEG) for low-latency data transmission.
- Cloud-based analytics for real-time alerts and risk assessment.

Operating on multi-layered city and building-level architectures, SFSMS was tested in South Korea's "A Building", where it demonstrated faster response times, improved occupant guidance, and better energy integration compared to traditional systems. The use of a semi-automated literature review pipeline enhances the relevance of our findings in a rapidly evolving field. As the body of scientific literature continues to expand at an accelerating pace, the timeliness of insight generation becomes increasingly important. Our reusable framework, grounded in AI-driven topic modeling, expert review, and structured gap extraction, demonstrates how domain-specific knowledge synthesis can be both efficient and scalable without compromising quality.

B. COMPARATIVE ADVANTAGES

Compared to traditional fully manual reviews, the semi-automated methodology adopted in this study offers a significant increase in both processing speed and thematic consistency. Manual reviews, while rich in interpretive depth, are inherently time-intensive and prone to inconsistencies when handling large and diverse corpora. On the other hand, fully automated reviews may produce rapid outputs but often lack domain sensitivity and contextual nuance. Our hybrid approach balances these trade-offs. Topic modeling with LLMs accelerates the identification of coherent research themes, while expert validation ensures conceptual rigor and contextual accuracy. This enables a high-throughput yet credible synthesis process, where speed does not come at the expense of insight depth or practical relevance.

C. LIMITATIONS

While the methodological framework presented in this study offers significant advantages in terms of efficiency, thematic consistency, and scalability, several limitations must be acknowledged. First, although state-of-the-art large language models (LLMs) were employed to generate topic clusters and support gap identification, these models are inherently

influenced by the data on which they were trained. Despite their remarkable generalization capabilities, certain inherent characteristics such as source imbalance, regional orientation, or terminological prevalence can introduce residual biases, which may in turn subtly influence the interpretation and classification of thematic content [120]. Consequently, the outputs of the LLMs should be critically reviewed, particularly when applied to domains with rapidly evolving or underrepresented research streams. Second, the assessment of inter-rater agreement using Fleiss' Kappa revealed levels of consistency ranging from fair to moderate. This outcome is interpreted in light of the instrument's status as a boundary object, shaped by the disciplinary and conceptual heterogeneity of the expert panel involved [130]. Nonetheless, it also underscores the need for a larger and more diverse group of raters to enhance statistical robustness—an objective often constrained by limitations of time, availability, and domain specialization. A particularly promising direction for future research lies in the integration of LLMs themselves as evaluators or adjudicators within expert review processes. Recent studies suggest that, when properly calibrated, LLMs can function as reliable and consistent second-opinion raters, potentially reducing the burden on human experts while preserving interpretive accuracy [121]. Finally, the literature sample used in this study was limited to English-language publications within a defined temporal window. While this constraint ensured manageable scope and language consistency, it may have inadvertently excluded relevant research contributions from other linguistic or regional communities. Expanding the dataset to include multilingual sources and broader temporal coverage in future iterations would enhance the representativeness and inclusivity of the review.

D. ITERATIVE UPDATES AND SCALABILITY

A key strength of the proposed framework is its capacity for iterative updates. As new research publications emerge, the pipeline can be re-executed with minimal effort to refresh topic clusters, update expert assessments, and re-identify knowledge gaps. This dynamic characteristic ensures that the state of knowledge remains current and that emerging trends or gaps are quickly recognized. Moreover, the modularity and scalability of the approach make it adaptable to other domains beyond smart building safety. With minimal customization, this framework could support evidence-based decision-making in adjacent fields such as disaster resilience, urban infrastructure, or sustainable construction; allowing for continual monitoring of knowledge production and alignment with evolving research priorities.

VI. CONCLUSION AND FUTURE WORK

The gap analysis conducted in this study reveals a multifaceted set of challenges that cut across the technological, operational, and social dimensions of smart building safety. From the extracted gaps, clear patterns emerge: the persistent lack of real-world validation for emerging systems, the absence of unified interoperability protocols, and the

TABLE 4. Roadmap and future direction per category.

Categories #	Road Map and Future Directions
Automation and Smart Systems	1. Develop advanced AI-driven early detection systems for fire hazards using multi-sensor data fusion to enhance accuracy and reduce false alarms. 2. Implement machine learning models to predict and prevent critical events such as electrical failures, optimizing IoT-based anomaly detection systems for predictive maintenance. 3. Design intelligent evacuation systems using real-time data analytics to dynamically guide occupants to safety during emergencies, integrating IoT sensors and AI for personalized escape routes. 4. Create advanced alert and information systems for first responders, incorporating AI-driven contextual maps and heat maps to improve emergency response efficiency. 5. Explore the integration of digital twin technology with building management systems to simulate and optimize fire safety and evacuation procedures in real-time. 6. Develop a unified framework for integrating various IoT devices and protocols to enhance interoperability and data sharing across smart building management systems. 7. Investigate the use of blockchain technology for secure and tamper-proof logging of sensor data in smart buildings, enhancing privacy and data integrity. 8. Enhance smart building systems with adaptive learning algorithms that can predict and adjust to changes in building occupancy and environmental conditions for optimized energy management and safety.
Cybersecurity	1. Develop advanced information systems for smart buildings that provide accurate and clear emergency information, reducing evacuation times and improving survival rates. 2. Implement AI-driven early detection systems in smart buildings to identify fire hazards using integrated sensors and machine learning algorithms, enhancing response times and accuracy. 3. Explore the integration of IoT devices with blockchain technology to enhance data security and privacy in smart city infrastructures, ensuring robust protection against cyber threats. 4. Design intelligent, segmented evacuation plans using real-time data analytics and machine learning to optimize escape routes based on the specific dynamics of each emergency. 5. Create advanced systems for providing intelligent alerts and contextual maps to first responders, utilizing AI to analyze real-time data from emergency sites for more effective interventions. 6. Investigate the use of edge computing in IoT-based fire detection systems to process data locally, reducing latency and improving the reliability of fire safety systems. 7. Develop a comprehensive framework for the integration of cyber-physical systems in smart buildings, focusing on enhancing security protocols and system resilience against cyber-attacks. 8. Enhance IoT-based fire alarm control panels with standardized protocols and dual connectivity to improve reliability and compliance with fire safety standards.
Digital Twin	1. Develop advanced AI-driven path-planning systems for fire rescue operations in multistory buildings, incorporating real-time data from IoT sensors and visual guidance technologies to dynamically adjust evacuation routes. 2. Explore the integration of machine learning algorithms with digital twin technologies to predict fire spread patterns and optimize evacuation strategies, enhancing safety and reducing response times. 3. Implement augmented reality (AR) training modules for fire safety education, focusing on interactive and immersive experiences to improve knowledge retention, motivation, and self-efficacy in building occupants. 4. Create a unified digital twin framework that incorporates real-time monitoring of fire safety equipment and structural integrity, using IoT and AI to predict and prevent potential fire hazards. 5. Develop intelligent control systems for building fire protection, utilizing semantic web technologies and digital twins for real-time decision-making in fire incidents, including automated control of sprinklers, fire doors, and smoke control systems. 6. Extend the application of 3D building modeling and BIM to support rapid generation of indoor models for emergency response, enhancing the accuracy of evacuation routes and situational awareness for first responders. 7. Design and test AI-based smart fire safety systems for urban environments, integrating fire detection, energy management, and optimized evacuation strategies to enhance overall safety and efficiency. 8. Enhance AI-driven tools for fire safety design, automating tasks from design drawing generation to fire detection and evacuation planning, thereby reducing manual errors and improving compliance with fire safety regulations.
Enhanced Connectivity and Integration	1. Develop advanced IoT-based systems for real-time monitoring and control of fire safety devices, ensuring improved reliability and effectiveness in diverse building environments. 2. Implement machine learning algorithms to enhance the predictive maintenance capabilities of smart building systems, focusing on energy management and safety enhancements. 3. Explore the integration of digital twin technologies with building management systems to simulate and optimize fire safety and evacuation procedures in real-world scenarios. 4. Design intelligent evacuation systems using AI to dynamically generate personalized evacuation routes based on real-time data and occupancy levels. 5. Create a unified protocol for IoT devices in smart buildings to ensure seamless communication and interoperability across different technologies and platforms. 6. Develop AI-driven early detection systems for environmental hazards such as smoke, fire, and toxic gases, integrating these systems with mobile and web applications for timely alerts. 7. Implement augmented reality (AR) applications to assist first responders in navigating complex building layouts during emergencies, providing real-time data overlay of the environment. 8. Enhance fire detection systems using deep learning models like YOLOv8 to identify and locate fire incidents in real-time with high precision and recall rates. 9. Investigate the use of sensor fusion techniques to improve the accuracy and reliability of IoT-based environmental monitoring systems in smart buildings. 10. Develop cost-effective sensorized devices with integrated data analysis capabilities for detecting and reporting multiple types of emergencies, such as fires, floods, and gas leaks.

TABLE 4. (Continued.) Roadmap and future direction per category.

Advanced Sensing Technologies	1. Develop advanced neural network models to enhance the accuracy and reduce false alarms in fire detection systems, leveraging multi-sensor data integration. 2. Implement real-time, camera-based fire detection systems using machine learning algorithms for large-scale environments, ensuring high accuracy and quick response times. 3. Explore the integration of environmental parameters like humidity and light into IoT-based smart building applications for more comprehensive and accurate real-time data analytics. 4. Create cost-effective, fiber optic sensor systems for structural health monitoring in smart homes, focusing on foundation integrity and environmental impact. 5. Develop digital twin frameworks for intelligent control of building fire protection systems, incorporating semantic web technologies for improved data interoperability and real-time decision-making. 6. Utilize deep learning algorithms such as YOLOv8 for smart fire detection systems in urban settings, aiming for high precision and adaptability to various environmental conditions. 7. Optimize sensor placement in buildings using simulation and data-driven technologies to enhance fire localization accuracy and cost-efficiency. 8. Integrate advanced computational models with fire detection systems to simulate real-time fire scenarios and improve the reliability and scalability of these systems. 9. Implement digital twins in building lifecycle management for predictive maintenance and anomaly detection, enhancing overall building safety. 10. Enhance gas sensor technologies in smart buildings for early detection of hazardous gases, focusing on selectivity, cost reduction, and integration with building management systems. 11. Develop intelligent evacuation systems using real-time sensor data and AI-driven crowd modeling to optimize evacuation strategies during emergencies. 12. Expand the capabilities of cyber-physical systems in smart buildings to support cognitively declined individuals, focusing on comprehensive applications, usability, and ethical standards.
Standard Compliance Management	1. Develop a sociotechnical systems (STS) framework for fire safety that integrates iterative communication among stakeholders such as engineers, regulators, and building operators to enhance resilience and adaptability in fire safety solutions. 2. Implement advanced tools for risk and systems analysis that incorporate social behaviors and stakeholder interactions to improve the robustness of fire safety designs. 3. Explore the integration of smart sensors and IoT technologies within the STS model to enhance real-time monitoring and adaptive responses in fire safety systems. 4. Design and validate fault-tolerant IP-based communication protocols for fire alarm systems to ensure reliability and compliance with international standards like EN 5. 6. Investigate robust hardware system architectures and connections between field automation and management levels in Fire Alarm Control Panels (FACP) to enhance system reliability. 7. Develop unified protocols for home automation systems to ensure seamless integration and interoperability across various communication technologies like ZigBee, WiFi, and GSM. 8. Implement advanced AI-driven tools for predictive automation and intelligent control in home automation systems to enhance energy efficiency and user convenience. 9. Establish a conceptual framework for Dwelling Fire Safety Evacuation (DFSE) that includes design fire scenarios, survival strategies, and safety measures, and use it to guide future data collection and development of safety models. 10. Standardize IoT implementations in FACP systems focusing on interoperability, security, and compliance with regulatory requirements to enhance fire safety management. 11. Integrate maintainability rules into data-driven fault detection and diagnosis systems for managing mechanical and electrical services in smart buildings to improve interpretability and real-world applicability. 12. Expand the use of AI in building fire safety design to automate tasks such as design drawing generation, fire detection, and evacuation planning, and to optimize performance-based design methods.
Sustainability and Energy Efficiency	1. Develop advanced IoT-based systems for real-time energy and water management in various building types to enhance sustainability and operational efficiency. 2. Explore the integration of reversible thermochromic materials in building construction to improve energy conservation and heat management, focusing on enhancing color stability and reducing dependency on external stimuli. 3. Implement AI-driven early detection systems for environmental hazards such as fire, smoke, and toxic gases using advanced sensor technologies and machine learning algorithms. 4. Design intelligent, segmented evacuation plans using AI and machine learning to analyze building layouts and occupant data, ensuring optimal safety during emergencies. 5. Develop a unified IoT platform using technologies like LoRa and BLE to integrate various building management systems, including emergency lighting and smoke detectors, to enhance safety and operational efficiency. 6. Create adaptive, self-powered sensor suites for real-time monitoring of air quality and structural health, incorporating self-healing and fault tolerance capabilities. 7. Investigate the use of AI and big data analytics for predictive maintenance and energy management in smart buildings, aiming to improve system reliability and reduce operational costs. 8. Enhance the functionality of agent-based Building Automation and Control Systems (BACS) by integrating advanced energy monitoring and machine learning models to optimize energy usage based on real-time data.

TABLE 4. (Continued.) Roadmap and future direction per category.

Specialized Applications	1. Develop advanced AI-driven algorithms for modular construction to enhance safety and efficiency, achieving at least a 20% reduction in project duration. 2. Implement multisensor detection systems combining smoke and heat sensors to increase fire detection accuracy to over 95%. 3. Explore the integration of cyber-physical systems with IoT for supporting cognitively declined individuals in smart buildings, focusing on increasing autonomy and reducing caregiver burden. 4. Design and test AI-based early detection systems for various emergencies (fire, smoke, electrical issues) using real-time data analysis and predictive modeling. 5. Develop intelligent, adaptive fire safety systems using dynamic system modeling and thermal imaging technologies to simulate and react to real-time fire scenarios in buildings. 6. Create personalized, AI-enhanced evacuation plans using building-specific data and occupant profiles to optimize safety during emergencies. 7. Implement AI-driven contextual maps and heat maps for first responders, enhancing situational awareness and decision-making in emergency scenarios. 8. Integrate advanced computational models with existing building management systems to improve the reliability and scalability of fire detection and suppression technologies. 9. Develop unified communication protocols for home automation systems to ensure seamless integration and interoperability across different technologies (ZigBee, WiFi, Bluetooth, EnOcean, GSM). 10. Explore the use of ontology-based frameworks for organizing critical data in emergency situations, ensuring quick access to essential information for first responders.
Decision Making in Smart Disaster Response System	1. Develop unified communication protocols for diverse home automation technologies to enhance interoperability and seamless integration. 2. Implement advanced AI algorithms for predictive automation in smart disaster response systems, focusing on early detection and intelligent control. 3. Explore energy-efficient solutions in home automation systems to promote sustainable living, aiming for a reduction in energy consumption by at least 30%. 4. Design and test an integrated framework using plithogenic set theory for evaluating the performance of smart disaster response systems under uncertainty. 5. Develop digital twin technology for real-time fire safety management, including evacuation planning and equipment maintenance, overcoming current technical and economic barriers. 6. Create AI-driven tools for real-time, dynamic hazard modeling integrated with 3D building models to improve evacuation and rescue operations during emergencies. 7. Implement IoT-based intelligent fire protection systems using 3D GIS and real-time data to optimize evacuation routes and rescue vehicle scheduling. 8. Explore the use of augmented reality for fire safety training to enhance learning outcomes, motivation, and self-efficacy among building occupants. 9. Develop ontology-based frameworks to provide structured, quick, and accurate access to critical building-related data for firefighters during emergencies. 10. Integrate machine learning models with IoT technologies to dynamically update fire evacuation routes in real-time based on environmental data and occupant locations.

underdevelopment of adaptive and intelligent response mechanisms. Extended gaps, derived through AI-supported inference, highlight deeper structural limitations such as the need for standardization across digital twin platforms, enhanced integration of AI in predictive maintenance and evacuation models, and the incorporation of ethical, privacy, and human-centered design considerations. Together, these findings not only confirm longstanding research deficiencies but also expose latent opportunities for innovation. They underscore the urgency of interdisciplinary collaboration and the importance of continuously monitoring the evolving technological landscape to ensure that smart buildings are not just more connected, but demonstrably safer, more resilient, and socially responsible.

The roadmap developed in this study provides a concrete and forward-looking trajectory for addressing the most critical needs identified in smart building safety research. Organized by thematic categories, it outlines actionable priorities such as developing AI-driven evacuation and hazard detection systems, advancing digital twin frameworks for

real-time emergency management, and designing interoperable platforms that unify fragmented IoT infrastructures. These proposed directions not only reflect technological aspirations but are also grounded in feasibility, with many initiatives leveraging existing AI, sensor, and connectivity capabilities. Furthermore, the roadmap encourages the integration of overlooked elements like blockchain for data integrity, augmented reality for first responder training, and cyber-physical systems tailored for vulnerable populations. By translating identified gaps into targeted development areas, the roadmap serves as a bridge between diagnosis and intervention empowering researchers, engineers, and decision-makers to coordinate efforts and allocate resources where they can have the most strategic impact.

In terms of the method, this study presents a novel hybrid methodology that integrates state-of-the-art large language models (LLMs) with expert validation to construct a comprehensive knowledge map of smart building safety research. By leveraging unsupervised topic modeling, structured gap analysis, and Fleiss' Kappa agreement metrics, the

framework offers both thematic depth and methodological transparency. The resulting map organizes a complex, multidisciplinary body of literature into coherent clusters, each annotated with domain-relevant summaries and actionable research gaps. This structured representation not only reflects the current state of knowledge but also enables stakeholders to navigate the landscape of fire, electrical, and life safety technologies with clarity and strategic insight. In an era where building systems are becoming increasingly interconnected and reliant on intelligent technologies, the ability to rapidly identify and prioritize research gaps is essential. This study demonstrates how semi-automated review pipelines can accelerate the discovery of unmet needs, ranging from real-time hazard detection and interoperability protocols to cybersecurity resilience and digital twin validation. The framework equips researchers, policymakers, and industry leaders with a scalable tool for evidence-based decision-making, enabling more timely and impactful advancements in smart building safety. Looking ahead, several opportunities exist to improve and expand the methodological pipeline. One immediate area for enhancement lies in refining the cluster labeling process by incorporating context-aware models or domain-specific ontologies, thereby improving naming precision. Furthermore, integrating alternative data sources such as patent records, standards documentation, or multilingual corpora could expand both the scope and the granularity of the thematic map.

Beyond technical refinements, the knowledge map offers a foundation for collaborative research initiatives that directly address the identified gaps. Interdisciplinary teams spanning engineering, data science, policy, and emergency services can use the map as a strategic blueprint for targeted innovation. As new literature emerges, the pipeline can be re-applied to ensure that research priorities remain aligned with evolving risks and technological capabilities, thereby supporting the development of a safer and smarter built environment.

APPENDIX A ROAD MAP AND FUTURE DIRECTIONS

See Table 4.

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