Internet of Things 22 (2023) 100803

Contents lists available at ScienceDirect

Internet of Things

journal homepage: www.sciencedirect.com/journal/internet-of-things

Review article

The role of IoT sensor in smart building context for indoor fire hazard scenario: A systematic review of interdisciplinary articles

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ARTICLE INFO

Keywords:
Internet of things (Iot)
Sensor
Indoor fire hazard
Smart buildings
Systematic review
Thematic analysis

ABSTRACT

In recent years, there has been growing interest in using Internet of Things (IoT) sensors to address indoor fire hazards in smart buildings. This study conducted a systematic review of 54 articles from interdisciplinary databases using selected keywords over the past decade, with the aim of investigating the potential role of IoT sensors in indoor fire hazard contingency. Through thematic analysis, five main themes and 24 sub-themes were identified, including vision-based sensing, smart automation, evacuation and indoor navigation, early fire detection, intervention and prevention, and BIM-related. The results of this review indicate that there are numerous aspects of indoor fire hazards that could benefit from the use of IoT sensors, and that the recurrence of technical terminologies in the analysed articles underscores the importance of these technologies in establishing an IoT sensor network in smart building environments, particularly in addressing indoor fire incidents. The outcome and findings spurred a concept for potential future research ideas. As a result of the findings, a conceptual framework for IoT sensors in the context of smart buildings is proposed.

1. Introduction

The recent virus outbreak, COVID-19, has reached almost every country worldwide and was declared a pandemic in March 2020 by the World Health Organization [1]. Indeed, as reported by mainstream media, it has severely impacted the global economy, stock markets, trading, and major industries such as manufacturing, health, construction, and many more. As the world is steadily recovering and moving forward post-COVID-19, the same can be said for the global economy and primary industries. According to a new market

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https://doi.org/10.1016/j.iot.2023.100803

Available online 30 April 2023

research report published by [2], the global building construction market is expected to grow slightly from US$ 5.88 trillion in 2020 to US$ 6.45 trillion in 2021, at a cumulative compound annual growth rate (CAGR) of 9.8%.[1] This growth is mainly due to the corporation's reshuffle of operations and recovery from the COVID-19 impact, which had previously halted as a consequence of the imposed restriction measures such as social distancing, virtual working, and the closure of numerous commercial activities that resulted in operational challenges. This statistical figure proves that the need to establish new buildings is still relevant despite of global outbreak. The traditional definition of buildings merely comprises structure and serves the purpose of providing shelter and security. However, the game has changed—thanks to emerging technologies. With technological advancement comes the expansion of numerous opportunities. The inception of the smart city concept, along with its prime enabler technologies, including Artificial Intelligence (AI), Machine Learning (ML), cloud computing, and Wireless Sensor Networks (WSN) [3], have heightened the traditional building concept into the smart building notion. The essential purpose of the building is amplified by the smart building idea, which can adapt to the broader environmental information at the core instead of reacting [4], such as monitoring occupant comfort and energy efficiency simultaneously [5] and automated enough to address water management, lighting systems, and fire detection [6]. The key to achieving this is fully utilising occupant-related and real-time environmental parameters [7]. To fully reap the benefits of a smart building, proper technology, as well as reliable sensing tools and other variables, were required. The rise of Internet of Things (IoT) based technologies bridges the gap in various fields [8]. A recent review by [9] stated that IoT is the building block of smart buildings where sensing and electrical components are monitored and controlled via a multiplex network. However, the review took a broad approach to its review, emphasising only the common sensors installed in smart buildings and ignoring the indoor hazard perspective. It is also reported that IoT applications are employed extensively in industrial, smart city, agriculture, buildings, and power management (citing a few), and the most progressing branch is industrial and smart city [8]. By integrating IoT, cloud, and fog technologies, an affordable prototype of a smart building was constructed by Dutta and Roy [10] to effectively control indoor functionalities. With IoT embedded in the building, users can monitor the building and have remote access to the recorded sensor information [11].

As previously mentioned, the prime objective of a building is to offer security and safety to its occupants. However, the safety of the building can be compromised by natural disasters or artificial factors [12]. Early intervention for certain man-made factors, such as indoor building fires, can be implemented using an indoor sensor to minimise losses. Currently, the state-of-the-art sensor embedded in the smart building allows for remote observation by the users. Remote monitoring aims to improve situational awareness provided that any hazardous incident occurs indoors. Statistically, over the past 23 years, the number of reported fires has remained relatively consistent across an average of 40 countries. However, the transition from 2019 to 2020 shows an upward trends, as reported by [13].

Meanwhile, global fire statistics for 2020 from 34 countries [13] highlighted that structural fire-based – specifically residential fires, including all other facilities- contributed to the highest percentage of 32.2%. A similar pattern can be seen domestically in Malaysia, as outlined in [14], where building fires ranked at number three (3), with 12%, as portrayed in Fig. 1. These structural fires not only caused property damage but also resulted in fatalities, injuries, and financial losses. According to [15], 78% of civilian deaths, 86% of injuries, and US$ 12.1 billion in property damage occurred in the United States of America in 2020. It is also worth noting that the fire department responded to a structure fire call every 64 s, while fire injuries occurred every 41 min, including fire death circumstances, which occurred every 3 ½ hours on average.

The growing figure of structural fires and their negative impacts require proper approaches to improve the safety of the inhabitants. In their literature review over a specific period, [12] suggested various strategies for enhancing fire safety. These strategies include utilising advanced analysis techniques to create visual or graphical simulations of emergency exits and fire-resistant structures. The above-mentioned strategy can be implemented and achieved using readily available current technology.

Correspondingly, this systematic review aims to explore the theme related to IoT sensors, indoor fire hazards, and smart buildings. The reported number of literatures focusing on indoor hazard in smart building using IoT sensor is assuring but there were still unsatisfactory number of researchers that systematically reviewed the present theme. Previous studies [9] have not dealt with indoor hazards in detail while [16] has reported the transition of cyber physical system to human cyber physical systems in smart building point of view. Thus, this review is meant to contribute to the body of knowledge by gathering ample information related to the theme. Basically, this review attempts to investigate the possible role of utilising IoT sensors for indoor fire hazard contingency in the smart building context. Moreover, potential research related to the context above will be proposed as a conceptual framework. In summary, the following research pillars govern this review: "How could the use of IoT sensors assist in the event of an indoor fire hazard within the scope of smart buildings?". Overall, this systematic review is constructed from 54 articles from notable interdisciplinary databases based on the keywords associated with the selected themes over the last decade. The remainder of this paper is structured as follows; Section 2: Methodology adopted to conduct this review; Section 3: Results comprises the summary of the literature review; Section 4: Discussion and potential future research conceptual framework and Section 5: Conclusion.

2. Methodology

A coherent systematic literature review (SLR)[2] entirely depends on the constructed research question. Therefore, the research

[1] CAGR in a simple term is a measure of the rate of growth of an investment or business over a period of time.It takes into account the fact that the growth rate of an investment or business can vary from year to year. By using a single number that represents the average annual growth rate over a period of time, CAGR makes it easier to compare the growth of different investments or businesses.

[2] A systematic literature review is a research method that involves searching for and analysing all existing studies on a topic to provide a comprehensive overview of the current state of knowledge. It's used to inform decision-making and guide future research.

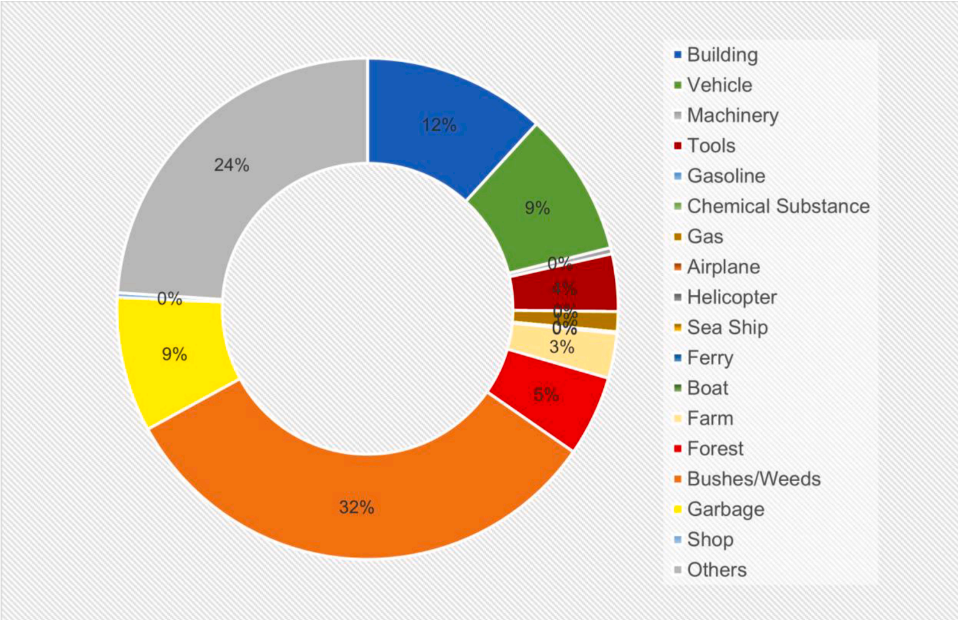

Fig. 1. Reported types of fire in Malaysia for 2020 adopted from [14].

question must be first established so the review will have a firm direction. Numerous frameworks and methods can be implemented to produce a “foreground” research question, such as PICO, PICOS, TOPICS +*M*, and SPIDER [17]. Each of these methods has its own directions and advantages.

As for the review guideline, this review adopts Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020[3] to help produce the appropriate outcomes in line with the main research question established earlier. Fundamentally, producing SLR as per PRISMA revolves around information identification, screening, and finalising the results. It is also essential to refer to credentialed academic databases and platforms to search for the information.

The whole approach to conducting this present SLR will be discussed in the forthcoming sections. Nevertheless, it starts with (1) formulating the right research question using the PICO template, (2) PRISMA and systematic search strategies, and (3) data extraction and synthesis.

2.1. *Defining the “right” research question*

A list of tools can assist researchers in formulating the right research question for academic writing. The authors have adopted the PICO template for this review to construct the “fitting” research question. PICO stands for Population, Intervention, Control, and Outcomes. [18] The reason behind separating and fractioning the question is to enable the classification of information related to the research [19]. PICO is widely used in framing research questions related to the clinical field. However, the framework is also proven to be suitable in non-clinical environments [20]. In composing the research questions for this review, the authors have refined and conformed to the following information, as constructed in Table 1.

As a result, the underlying research question for this review is "How could the use of IoT sensors assist in the event of indoor fire hazards in smart building surroundings?" based on the context and ideas gathered using the PICO template.

2.2. *PRISMA and systematic searching strategies*

Initially, PRISMA 2020 was introduced to accommodate systematic reviews related to health interventions. However, the checklist is still valid in other fields regardless of whether you are reporting any intervention or whether it involves synthesis or non-synthesis. Therefore, it is suggested to use PRISMA 2020 at the early stage of literature review as the checklist provided will assist in ensuring an ambiguous, comprehensive, and precise review [21]. Overall, it comprises seven sections with a total of 27 items on the checklist and supplies a checklist for abstract statements [21]. Apart from that, it also supplies a flow diagram for the literature screening process. Therefore, the entire process of exploring references was conducted per PRISMA procedures. Consequently, it can be organised into the following steps.

[3] PRISMA is a set of guidelines for reporting systematic reviews and meta-analyses, developed in 2009 and updated in 2020. It provides a checklist and flow diagram to improve the transparency and accuracy of research synthesis.

Table 1
PICO template for composing research question.

PICO	Description	Topic
P (*Population or Problem*)	Identify what the specific problem is.	Indoor fire hazard
I (*Intervention or Interest)*	Address what is the intervention or interest in dealing with the problem	IoT sensor-related
Co (*Context/Outcome*)	The final context or outcome expected from the defined problem and proposed intervention	Smart building/ Smart building Management

2.2.1. Information identification

The identification process involves using the right keywords to gather related articles and information. The key to populating the accurate keyword is to use the research question as the founding pillar so that it will not diverge from the intended objective. Hence, the search strings for this review were formed following the research question and linked using appropriate Boolean operators. The initial possible keywords identified were "building hazard, indoor hazard, indoor fire hazard, sensor, IoT sensor, smart building, smart building application, smart building management," which were narrowed down to form the search strings. Once the search strings have been formed, the search must be performed on well-established platforms. Then, the required articles were screened in these academic databases: Web of Science (WoS), Science Direct, Industry, Electrical and Electronics Engineers (IEEE), and Scopus. Except for one, three databases used identical search strings to adapt to the search requirement. Table 2 lists the search strings for each of the databases.

2.2.2. Information screening

Once the search strings and databases were formed and selected, additional steps needed to be included. It is essential to practice inclusion and exclusion criteria while screening to help narrow down the results. For this, it was equally determined that the search must only include English language and articles within the timeline of 2012 to 2022. The checklist also includes the type of paper and the type of publication. Only the article and review paper were selected as primary references and excluded grey literature. The justification is to assure the quality of the literature, as grey literature is a broad range of information published outside conventional publishing and distribution mediums and is often not well represented in indexing databases. As for the publication type, journal articles and indexed conference proceedings were selected as per Fig. 2, but precedence is given to journal articles as they are formally reviewed and indexed, as shown in Fig. 3. Apart from that, these steps also include selecting publication topics so that only related topics are covered. As soon as the information is retrieved, it requires duplication checking because the search was done in four different databases and might produce overlapped results. The inclusion and exclusion criteria will improve screening techniques and yield significant results. Table 3 summarises the information screening related to this review.

2.2.3. Information eligibility

The screening process will produce an abundance of results from the databases. Despite using the inclusion and exclusion criteria, the results provided require further verification. This is to determine whether the documents are eligible and valid for reference per the research question. It involves human intervention as it requires manual screening. First, eligibility checking starts with screening the title and abstract. Next, only full-text documents were considered for further reading. Following that, the chosen documents were screened thoroughly to determine if the content did not match the research question and direction of the review.

2.2.4. PRISMA 2020 flow diagram

Fig. 4 was slightly adapted to depict the process of conducting a systematic literature review. The process starts with formulating the research question, followed by gathering and screening information, and then determining the eligibility of the information. During the identification phase, a total of 800 articles were found from the databases. Before screening, reference management tools were used to remove 77 duplicate articles. Of the remaining 723 articles, 502 were excluded in the first screening phase due to a lack of relevant keywords such as fire, smoke, and hazard in the content. This left 221 articles for further review, which were screened based on their titles and abstracts. A second filtration process identified 79 eligible articles, but 25 were later removed due to irrelevancy after reading their full content. In the end, 54 articles were used as key references for the research.

Table 2
Databases and search strings.

Databases	Search Strings	Field Code
WoS	(("sensor*" OR "IoT sensor*") AND (smart building * fire application OR smart building fire OR indoor hazard* OR indoor fire hazard*))	ALL FIELDS
Scopus		TITLE, ABS, KEY
IEEE		ALL METADATA
Science Direct	(("sensor" OR "IoT sensor") AND (smart building fire application))	ALL FIELDS

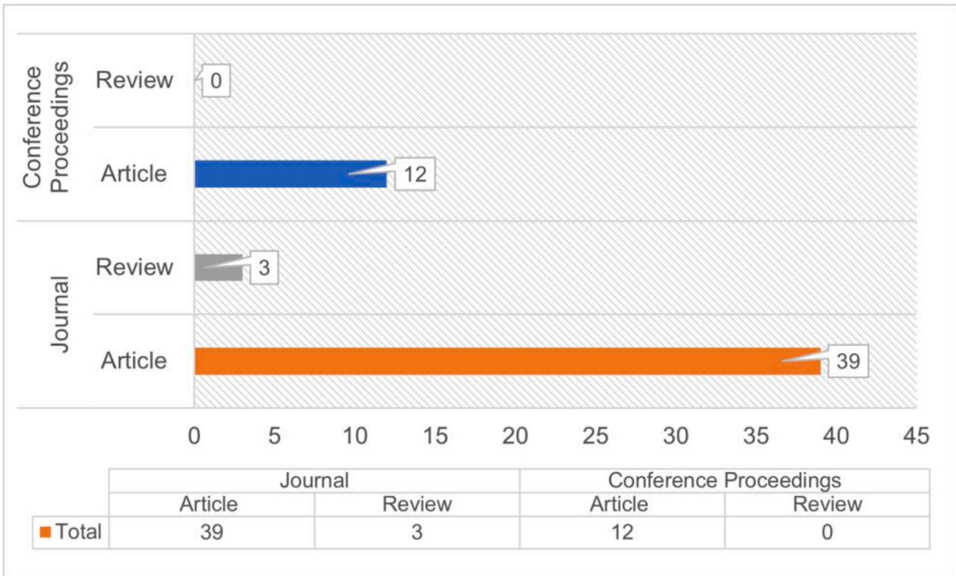

Fig. 2. Type of publications used in this SLR.

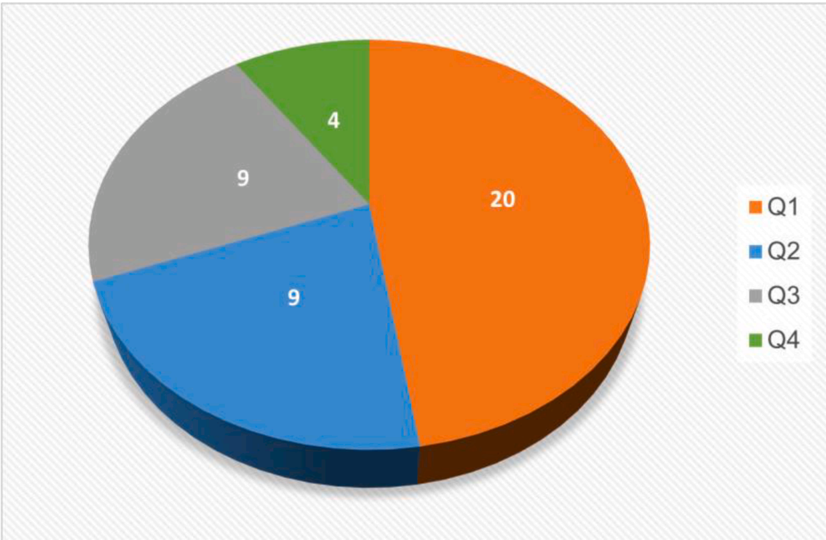

Fig. 3. Journal article rank indexed by WoS.

2.3. Data extraction and synthesis

The most crucial part is conducting the data extraction and synthesis. The extraction and synthesis processes are subjective; therefore, it is best to refer to legitimate guidance so that the writing will not divert from the paper's aim and research question. There are many synthesis techniques, including narrative summary, thematic analysis, meta-study, and qualitative meta-summary [17]. Thematic analysis was chosen for this paper because of its flexibility [22] and because the paper is structured by classifying and highlighting repetitive topics from the source of information [17]. The whole process started with skimming through the whole article, with emphasis given to the title, abstract, and, most importantly, the results and discussion section. Then, based on the deduced content, it is segregated into themes related to the research questions. First, the articles' most recurring topics and patterns were selected as the central theme. Subsequently, the main theme was evaluated and micro-pooled into another sub-theme. The authors have divided the findings into five themes and 24 sub-themes for this stage. In addition to thematic analysis, the review reported the most frequently occurring technical jargon associated with these themes in order to gain a bird's-eye view and connectivity on each theme.

Table 3
Summary of information screening.

Databases	Criteria Language	Timeline	Type of paper	Type of publication	Research Area/Topics/Field
WoS	English	2012–2022	Article Review paper	Journal article Conference proceedings	Engineering, Computer science, Environmental Science ecology, Construction building Technology, Public environmental Occupational health, Automation control system
Scopus					Nil
IEEE					Internet of Things, Building, Management systems, Wireless sensor Networks, Emergency Management, Indoor environment, Gas sensor, Fires, Learning (Artificial Intelligence), Health hazards, Emergency services, Temperature sensors
Science Direct	English	2012–2022	Article Review paper	Journal article Conference proceedings	Renewable and sustainable energy Reviews, Future generation Computer system, Automation in construction

3. Results

A total of 54 articles were chosen for the purpose of review, covering the time period from 2012 to 2022. Fig. 5 presents an overview of the primary thematic classifications and sub-themes identified in the articles. It should be noted that each of the 54 articles may cover multiple themes rather than being restricted to a single theme. Furthermore, under each theme, the articles may explore several sub-themes. To enhance the understanding of these themes and their practical applications, this section offers an in-depth analysis of the five primary themes and 24 sub-themes. To see the correlation between each article and its associated central theme and sub-themes, Table 4 presents a comprehensive list of the articles and their corresponding main themes and sub-themes.

3.1. Vision-based sensing

Currently, detecting indoor fire hazards solely relies on fire detection systems that identify changes in temperature readings, smoke, or signs indicating fire presence. The system's operational capabilities are primarily influenced by a couple of elements – the device itself and the implementation of the algorithm [23]. Thus, any setback of the two factors and the improper placement and distribution of the fire detection systems in a larger space or area would contribute to the false alarm scenario [23,24]. Many researchers have proposed using a vision-based sensor (VBS) to overcome the problem. It is widely used in addition to traditional sensing systems as an extra precautionary measure to confirm a fire situation and, as a result, reduce the false alarm rate. Several studies investigating VBS sensing methods have been carried out in the past few years, beginning in 2018. The proposal has shown diversified usage of VBS methods for fire incidents. In exploring methods to assist individuals with visual impairments, [24] has taken a comprehensive approach by proposing the use of smart glasses capable of distinguishing between hazardous and non-hazardous fires. This concept utilises artificial intelligence (AI) in combination with a deep convolutional neural network (CNN), specifically employing the YOLOv4 model due to its ability to customise image resolution. In the same vein, [25] used AI as an approach to provide visual sensing to detect fire. However, instead of using smart glasses, the deep learning consisted of image datasets from MIVIA, FIRESENSE, and CAIR that were processed on the Raspberry Pi 3B+.

On the other hand, [26] has proposed indoor positioning using computer vision in lieu of the commonly used GNSS for indoor positioning. Like the previous researchers, [26] underlined that using the computer as VBS requires deep learning; in this case, AlextNet is the CNN and inertial measurement unit (IMU) intervention to ascertain trapped evacuees. During fire incidents, evacuees can use their mobile phones to capture the surrounding image, activating the rescue path.

In addition to assisting trapped evacuees, the proposed VBS method has met the needs of firefighters. Currently, most of the search and rescue (SAR) for indoor fires relies entirely on 2D-based strategies that provide minimal information and are less effective. To aid firefighters in search and rescue (SAR) missions, [27] combined several advanced technologies, one of which involves real-time visualization guidance for firefighters during rescue operations. This system integrates Bluetooth, building information modelling (BIM), and SQL server technologies to provide real-time visual and audio guidance from the incident commander to the firefighter inside the building via mobile phone apps. The incident commander refers to BIM visual information and relays this information to the firefighter on duty, enabling them to receive vital guidance and assistance during the mission. Another researcher has used a mobile phone as a device for the VBS method. As a means of providing intelligent routing guidance during fire emergencies, [28] proposes the development of a mobile application capable of notifying evacuees of a fire emergency and providing them with visual and audio

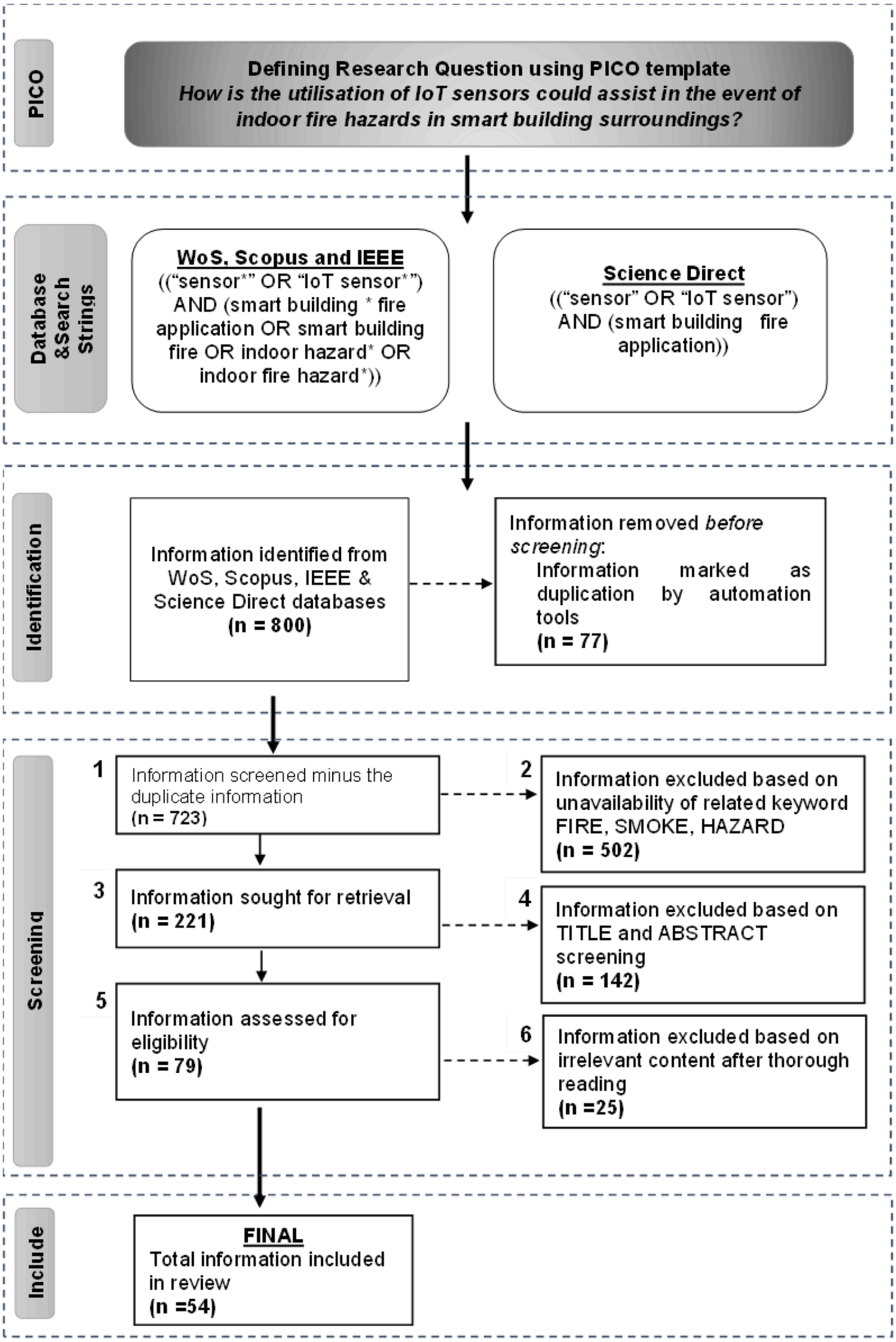

Fig. 4. PRISMA workflow diagram.

guidance. The application employs a web server to determine the optimal routing path for the user, transmitting environmental photos and navigation signs to guide them to safety. Additionally, the researcher incorporates radio-frequency identification (RFID) technology to determine the location of trapped evacuees, further aiding the rescue operation.

The use of the VBS method displays a lot of beneficial factors. However, it still has its impediments and disadvantages. An investigation into VBS [23] found an approach to conserving occupants' privacy while detecting fire using the VBS method. As VBS revolves around visualising environmental surroundings, privacy issues must be tackled. The concept has customised the NIR camera

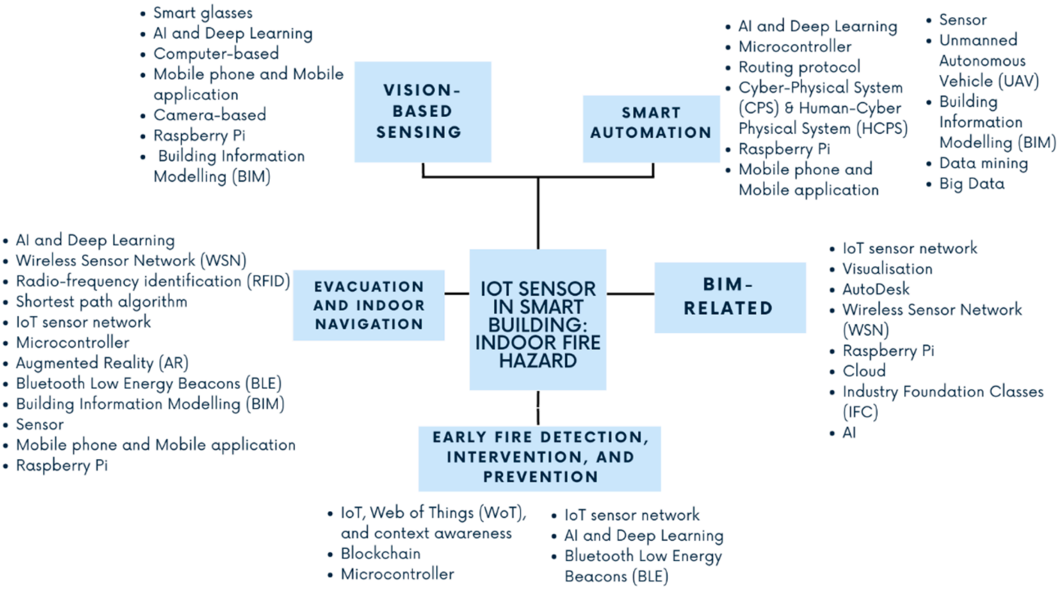

Fig. 5. Overview of the thematic classification and sub-themes in the articles.

and trained the camera using a spatially aware fire detection system (SA-FDS) SA-FDS [23], a form of CNN. The SA-FDS is a modified version of SqueezeNet. The framework is called ST-FDS, combining and customising SA-FDS and distance formula to detect fire or non-fire situations. Further efforts to preserve privacy were made by assessing the privacy level and concluding that privacy level 4 is acceptable for fire detection using the customised camera.

3.2. Smart automation

According to the comprehensive review written by [6], automation in a smart building is essential in line with technological advancement and availability, as automation will expedite real-time parameter interconnection and improve decision-making during harmful situations. The review also discussed on the use of low-cost sensors and IoT technology to collect data and transmit it to central control stations. The branch of smart automation is vast, but one area that warrants attention is the integration of automated fire detection systems in buildings, using an evacuation algorithm and low-cost IoT sensors for early fire detection. This area is closely connected to both the Internet of Things (IoT) and cyber-physical systems (CPS), which share similarities and intersect with each other [29]. The term CPS was first coined in 2006 to describe the seamless merging of computational algorithms with real-world components [16] This is clearly illustrated in [30], where the smart system comprises a sensor network, cloud server, and AI engine with a user interface to detect fire and simultaneously predict the fire's position and size. The AI engine is formulated using long short-term memory (LSTM), a recurrent neural network (RNN) branch, and a trained mathematical database. Aside from fire detection, an attempt was made to develop an intelligent fire extinguisher using NodeMCU as the microcontroller, phyton coding, sensors, and camera for detection and subsequently verifying the fire to reduce false alarms [31]. Once the fire situation is confirmed, the controller will send a signal to the DC motor and activate the water pump to extinguish the fire. In their study, [32] put forth the concept of employing ESP8266, a backpropagation (BP) neural network, and Arduino UNO for remote and real-time monitoring of smart homes. The proposed approach presents an innovative solution for monitoring various aspects of smart homes in a seamless and efficient manner.

The critical aspect of IoT and sensors is the use of the routing protocol. The routing service ensures efficient information communication amongst smart things and internet nodes. Therefore, the Internet Engineering Task Force (IETF)[4] created a routing protocol specifically for IoT usage, called the IPv6 routing protocol for low-power and lossy networks (RPL) [33]. However, there is no specific routing protocol designed to cater to fire-sensor related as it involves real-time effective data transfer. Due to this reason, [33] attempted to develop an emergency RPL (EMRPL) with the functionality to anticipate the fire trajectory and relay the sensor information in real-time. The system's performance is evaluated based on the packet delivery ratio. The simulation reveals that EMRPL operates better than RPL in terms of packet delivery ratios, which are an essential factor in real-time fire incidents.

The scientometric review of the smart building has discovered the transition from traditional CPS to a human cyber-physical system (HCPS) that involves human interaction, whether directly or indirectly [16]. Although most of the proposed system or framework is fully automated with the use of IoT sensors and AI, it still requires a human approach, particularly in the fire hazard context, as it

[4] The IETF is a worldwide group of network experts who collaborate to develop and refine Internet standards and protocols. Its members are committed to ensuring the smooth operation and evolution of the Internet and have developed critical protocols such as TCP, UDP, and HTTP.

Table 4
List of selected articles with main themes and sub-themes.

Themes	Paper	Sub-themes (Application)
Vision-based sensing	[24]	Smart glasses
	[24–26]	AI and Deep Learning
	[26]	Computer-based
	[26–28]	Mobile phone and Mobile application
	[23]	Camera-based
	[25]	Raspberry Pi
	[27]	Building Information Modelling (BIM)
Smart automation	[30,32,37]	AI and Deep Learning
	[31,32,34]	Microcontroller
	[33]	Routing protocol
	[16,29]	Cyber-Physical System (CPS) & Human-Cyber Physical System (HCPS)
	[34]	Raspberry Pi
	[35,38–40]	Mobile phone and Mobile application
	[36,44] [6]	Sensor
	[43]	Unmanned Autonomous Vehicle (UAV)
	[41,42,45]	Building Information Modelling (BIM)
	[46]	Data mining
	[47]	Big Data
Evacuation and indoor navigation	[26,28,49,60,63]	AI and Deep Learning
	[50,51,55–57]	Wireless Sensor Network (WSN)
	[51,61]	Radio-frequency identification (RFID)
	[27,41,49,52–54]	Shortest path algorithm
	[55]	IoT sensor network
	[57,60]	Microcontroller
	[58]	Augmented Reality (AR)
	[60]	Bluetooth Low Energy Beacons (BLE)
	[59]	Building Information Modelling (BIM)
	[62]	Sensor
	[48,58]	Mobile phone and Mobile application
	[62]	Raspberry Pi
Early fire detection, intervention, and prevention	[37,48,64]	IoT, Web of Things (WoT), and context awareness
	[65]	Blockchain
	[65–68,70]	Microcontroller
	[72]	IoT sensor network
	[46,67,69–72]	AI and Deep Learning
	[72]	Bluetooth Low Energy Beacons (BLE)
BIM-related	[45]	IoT sensor network
	[27,42,72–74]	Visualisation
	[41,59,74]	AutoDesk
	[71,73]	Wireless Sensor Network (WSN)
	[41]	Raspberry Pi
	[74]	Cloud
	[26]	Industry Foundation Classes (IFC)
	[74]	AI

revolves around human life. Human intervention includes authority, judgement, and actions that encompass input, feedback, and manipulation that can improve the smart automation process. Human intervention is critical, as [34] has proposed an alert system known as SB112 involving city authority operatives to collect and operate vital information from the established smart city platform and public safety answering point (PSAP). The system's overall architecture starts with a low-cost but efficient sensor that collects and detects early fires and gas leaks based on an ESP32 microcontroller and Raspberry Pi 4 that send the data to edge computing -DECIoT for gathering, filtering, and aggregating data. Then, DECTIot will send the information to the smart city platform built on Apache Kafka and initiate a NG112 emergency call. Likewise, [35] requires a human role in the inLoc system that seeks to assist the elderly user during emergency egress, which has an administrator role in connecting and transferring the sensing data between the gadget and beacons.

Many researchers focused on automated early fire detection using IoT sensors as the primary foundation, but with a different implementation framework to establish its own novelty. For example, [36] proposed real-time temperature, humidity, and smoke detection coupled with a passive infrared (PIR) sensor for motion detection with visualisation ability. The same sensing concept was applied by [37] but with extra capacity to identify early fire outbreaks using weighted dynamic time warping (WDTW) as the fire detection algorithm. One of the purposes of having a smart fire system is to expedite the alarm notification to stakeholders, and [38] is using a global system for mobile communication (GSM) – email once the sensor threshold reading exceeds the limit.

Similar to VBS, smart automation could also accommodate fire personnel, and [39–42] has featured the smart decision system to guide and assist the fire personnel during a rescue operation. The three-tier-model system architecture by [39] was designed based on a few factors: the system's availability must be 24/7, capable of handling a mass amount of data, and highly scalable. On the other hand, [40] has proposed five components: a smart box, a back-end server, a middleware, front-end application, and a mobile application to

Table 5
Performance evaluation metrics from selected articles.

Paper	Performance Evaluation Metrics								
	Accuracy/Precision	Sensitivity	False Positive Rate	Response Time/ Evacuation Time	Scalability	Robustness	Energy Efficiency	Cost Effective	Privacy/Security
[6]	x	x	x	x	x	x	x	x	x
[16]	x	x	x	x	x	x	x	x	x
[23]	Fire detection technique using Spatio-Temporal Fire Detection System compared to other technique is 98.13%	x	x	x	x	x	x	x	A larger clarity index indicates a more clear image, while a smaller clarity index indicates a less clear image
[24]	Shows an improvement over other well-known approaches in all fire detection metrics such as precision, recall, and average precision	Shows high sensitivity in detecting fires in indoor environments	x	Experimental results show that it can detect fires in indoor environments with high low latency	x	Experimental results show that the system can detect fires in various indoor environments with different lighting conditions and object occlusions	x	x	x
[25]	The system integrates nonvisual and visual fire detection techniques to improve the accuracy of fire detection	x	The system aims at the early detection of fire with fewer false positives	x	x	x	x	x	x
[26]	Generate a safe and reliable rescue route with positioning error within 1.8 m	x	x	x	x	x	x	The framework is passive, cheap, and convenient, but does not provide specific numbers or figures related to cost effectiveness	x
[27]	The system provides real-time updates for optimal path planning in a dynamic environment, providing accurate information	x	x	x	If the path-planning range needs to be expanded to cover an entire building or other complex spatial forms, the system should be reconfigured	x	x	x	x
[28]	Has an accuracy of 98.1% for predicting risk levels of links	x	x	x	x	x	x	Low-cost and low resource-consuming system	x
[29]	x	x	x	x	x	x	x	x	x

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Table 5 (*continued*)

Paper	Performance Evaluation Metrics Accuracy/Precision	Sensitivity	False Positive Rate	Response Time/ Evacuation Time	Scalability	Robustness	Energy Efficiency	Cost Effective	Privacy/Security
[30]	AI model attained overall accuracy of 98% in predicting the tunnel fire scenarios	x	x	The total time delay is around 1 s from the on-site measurement of temperature to the final display of the tunnel fire scenario on a remote user interface	x	A filter algorithm is adopted to pre-process and interpolate the raw data in case of broken sensors to improve the robustness of the AI engine	x	x	x
[31]	x	x	x	x	x	x	x	x	x
[32]	x	x	x	x	x	Designed to be robust and can detect abnormal conditions in real-time	X	X	Designed to ensure the privacy and security of the users' data.
[33]	x	x	x	EMRPL reduces the time taken to rebuild the record but does not provide any specific numbers or figures related to response time or execution time	x	EMRPL can effectively increase the packet delivery ratio.This suggests that EMRPL is robust in such scenarios.	x	x	x
[34]	x	x	x	Able to detect a fire in real-time and with low latency (average latency of 32 ms).	Can be integrated with a smart city platform and relevant operators in an end-to-end manner for real-world scenarios.	Continuous and stable operation of the system is necessary in order to prevent fire from spreading, or unwanted situations associated with gas leakage.	x	x	x
[35]	Can detect a threat and guide the elderly user with a minimum 85.47 cm and maximum 239.8 cm distance error	x	x	x	x	x	x	x	x
[36]	x	x	x	x	x	x	x	The system is low-cost	x
[37]	Detection system achieved a high detection rate of 98.5%	x	Detection system achieved a low false alarm rate of 1.5%.	Fire detection algorithm was able to detect fires in real-time with a response time of less than 1 second.	x	Fire detection system was able to detect fires under various fire scenarios and	x	x	x

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Table 5 (*continued*)

Paper	Performance Evaluation Metrics Accuracy/Precision	Sensitivity	False Positive Rate	Response Time/ Evacuation Time	Scalability	Robustness	Energy Efficiency	Cost Effective	Privacy/Security
						environmental conditions			
[38]	x	x	GSM module is used in the proposed system to overcome false alarms	x	x	Designed to ensure monitoring of the lab and to solve security issues like fire detection	Has low power consumption	More cost-effective compared to existing systems	Designed to enhance the security of the lab by sending an alert email to users in case of an attack
[39]	x	x	x	x	x	x	x	x	Used the built-in methods available in Firebase, "Firebase Security Rules"
[40]	x	x	x	x	Use load balancer that constantly monitors the workload of each node and makes routing decisions based on this data to direct packets to nodes with lower workloads.	x	x	x	x
[41]	x	x	x	Provides real-time and dynamic fire information in 3D, which can support efficient evacuation	x	x		Designed to be cost effective but no specific details	The paper claimed to have high security but no specific details were discussed
[42]	The proposed algorithm yielded an average room-level accuracy of 87.1%	x	x	x	x	The algorithm was found to be robust against partial loss of deployed nodes	x	x	x
[43]	Programmed to collect proximity data from a beacon for 30-s periods, then to calculate the median proximity value of that data	x	x	x	x	x	x	x	Secure communications between UAVs, smart sensors, the control server, and a smartphone app for security managers
[44]	x	x	x	x	x	x	x	The proposed system is proven to be 33% cheaper than traditional design solution	x
[45]	The BIMSL was found to be more effective, efficient,	x	x	The results showed that BIMSL was faster than Java in	x	x	x	x	x

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Table 5 (*continued*)

Paper	Performance Evaluation Metrics Accuracy/Precision	Sensitivity	False Positive Rate	Response Time/ Evacuation Time	Scalability	Robustness	Energy Efficiency	Cost Effective	Privacy/Security
	and usable than the standard existing alternatives for integrating sensor data with BIM models			completing the task given					
[46]	The prediction accuracy of incidents using data mining techniques was found to be around 60% due to several factors	x	x	x	x	x	x	x	x
[47]	Efficiency is measured in terms of processing time and throughput, demonstrates the performance superiority of the proposed architecture	x	x	x	Architecture is scalable to handle different data processing algorithms and analytical packages	x	x	x	x
[48]	x	x	x	The system proposed an evacuation method but no evacuation time was mentioned	x	x	x	x	x
[49]	Modified model has a higher error rate compared to the original model due to trade-off between convenience and accuracy	x	x	x	x	x	x	x	x
[50]	Can provide accurate information on people density within building areas	x	The proposed algorithm has a positive false rate of 0.1	x	Can be integrated into existing low-bandwidth in building communication systems	x	Sensor nodes are designed to be energy-efficient, with a battery life of up to 2 years	x	x
[51]	x	x	x	x	x	x	x	x	x
[52]	x	x	x	ECSSN algorithm outperforms existing	x	x	x	x	x

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Table 5 (*continued*)

Paper	Performance Evaluation Metrics Accuracy/Precision	Sensitivity	False Positive Rate	Response Time/ Evacuation Time	Scalability	Robustness	Energy Efficiency	Cost Effective	Privacy/Security
				algorithms in terms evacuation time					
[53]	Results showed that it was able to calculate the shortest safe path from unknown points in a building to the closest exit points, excluding unsafe paths	x	x	x	Can be applied to buildings of different sizes and shapes	Can exclude unsafe paths and calculate the shortest safe path from any point in a building to the closest exit points	x	x	x
[54]	Can guide evacuees more effectively towards fire exits, resulting in a higher percentage of evacuees reaching the exit in less time	x	x	x	The authors state that the algorithms are designed to be scalable and energy-efficient	x	x	x	x
[55]	The mean error of fire detected time prediction ranges from 0 to 50 m is smaller than 5 s. The mean accuracy of the fire detected time prediction is 89.1%	x	x	x	x	The proposed system uses Available Egress Duration (AED) so that people can escape with higher probability.	x	x	x
[56]	x	x	x	x	x	x	x	x	x
[57]	x	x	x	Less than 4 s to update the entire SISES system installed at a 3392 m^2 building	x	Can communicate reliably in various conditions.	x	Cost-effective alternative to traditional smart exit sign systems that require a central server	x
[58]	Provides "information accuracy" as one of the factors that contribute to user satisfaction	x	x	More rapid than the existing system in terms of total extinguishment and evacuation time	x	x	x	x	"Security and Integrity" are factors that contribute to user satisfaction
[59]	x	x	x	Efficiently calculate recommended and negated directions to respond to a fire emergency with real-time information	Can be applied to different types of buildings and can handle a large number of exit signs	Designed to handle different types of hazardous areas and can provide real-time information to	x	x	x

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Table 5 (*continued*)

Paper	Performance Evaluation Metrics Accuracy/Precision	Sensitivity	False Positive Rate	Response Time/ Evacuation Time	Scalability	Robustness	Energy Efficiency	Cost Effective	Privacy/Security
						respond to a fire emergency			
[60]	Able to estimate the distance of an arbitrary occupant to within about four meters of their actual location	x	x	x	x	x	x	x	x
[61]	x	x	x	Designed to provide real-time solutions.	Designed to be scalable and can be extended to cover larger areas	Designed to be robust and can handle radio interferences and hazardous environments	Designed to be energy-efficient by using low-power sensors and optimizing the communication protocols	x	Designed to ensure the privacy and security of the firefighters' data by using encryption and authentication techniques
[62]	The measurement and identification of BMI using weight sensors, height detectors, and pedestrian identification devices are simple and accurate	x	x	x	The paper suggests that the proposed solution can be used in underground spaces prepared for construction or renovation	x	x	Using weight sensors, height detectors, and pedestrian identification devices are relatively low in cost compared to engineering construction	Avoids stealing personal privacy information and does not invade personal privacy
[63]	Efficiently and accurately guides evacuees to a safer location while significantly reducing direct fire exposure	x	x	Uses an energy-saving mechanism to reduce the response time/execution time	Framework is scalable and can be used in smart building advancements	x	Uses an energy-saving mechanism to reduce energy consumption	x	x
[64]	x	x	x	x	x	x	x	x	x
[65]	x	x	x	x	x	x	Uses a 950–50 ms sleep-wake cycle configuration to limit power consumption, allowing the system to consume on average only 9.8 mW	Does not require additional electrical installation, thereby lowering homeowner costs.	x
[66]	x	Discussed about the sensitivity of flame sensors at different environments with different brightness	x	x	x	x	x	x	x

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Table 5 (*continued*)

Paper	Performance Evaluation Metrics Accuracy/Precision	Sensitivity	False Positive Rate	Response Time/ Evacuation Time	Scalability	Robustness	Energy Efficiency	Cost Effective	Privacy/Security
[67]	Achieved a classification accuracy of 98.88% for three hazardous gases using an e-nose with a mixing chamber	x	x	x	x	x	x	x	x
[68]	Includes a complete weather station that can provide accurate forecasts for temperature and wind	x	x	x	x	x	Uses photovoltaic solar panels for energy purposes	Uses a PC instead of a microcontroller, which allows for more computing power at a marginal added cost	x
[69]	Uses fuzzy logic inference systems to process data from four sensors, which improves the reliability and accuracy of the information provided	x		x	Based on wireless sensor network technology, which can be easily scaled up or down depending on the size of the smart home	Uses multiple sensors to detect the level of fire danger, which makes it more robust than traditional fire detection systems	Implements a sleep scheduling method that can reduce battery resource usage, making it more energy-efficient than traditional fire detection systems	x	x
[70]	Discover fire events with an average accuracy value of 99.83% when taking 10% instances as the training dataset	Achieves high recall rate of 99.6%	x	x	x	x	x	x	x
[71]	Predicting accuracy of 94% when sensors were deployed throughout the tunnel with a separation of 1 m.	Sensitivity analysis is only done to optimise the database configuration	x	x	x	x	x	x	x
[72]	Detection metrics used in the proposed algorithm have a lower than 90% accuracy due to the moving camera	x	x	Firefighters arrived at the fire source 6 min earlier on average when using the proposed system	x	x	x	x	x
[73]	x	x	x	Low-latency message passing capability can be considered as a good response time	System could process data quickly, with an expected turnaround time of approximately	x	x	x	x

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Table 5 (*continued*)

Paper	Performance Evaluation Metrics								
	Accuracy/Precision	Sensitivity	False Positive Rate	Response Time/ Evacuation Time	Scalability	Robustness	Energy Efficiency	Cost Effective	Privacy/Security
				for real-time fire monitoring and sensor-assisted firefighting	1.0 ms for data measured at a frequency of 1.0 Hz				
[74]	x	x	x	Can significantly reduce the fire alarm response time, but no further elaboration	x	x	x	Claims that the system can reuse traditional FAS and upgrade existing buildings effortlessly with its BIM model	Private fire alarm data sharing problem by using the IEEE 1824 standard, which contributes to addressing the privacy/security issue

configure the system. Furthermore, [41] developed locating/fire modules that provide rescue navigation maps in BIM 3D visualisation. As for [42], the research presents an algorithm to precisely locate indoor evacuees and provide indoor visualisation to fire authorities. The algorithm is constructed based on the environment-aware radio frequency beacon deployment algorithm for sequence-based localisation (EASBL), which applies Tabu search as its metaheuristic parameter.

Apart from indoor monitoring, some researchers facilitate indoor and outdoor monitoring. For instance, [43] used sensor integration, unmanned aerial vehicles (UAV), the AIIJoyn IoT platform, and beacons. The proposed method is named UAV-assisted emergency monitoring and response (UAV-EMOR) and offers an active observing perspective while emphasising secure communication amongst its modules using fingerprint recognition. Meanwhile, [44] developed an all-around sensor prototype that supports five sensing functions using only three sensors. However, it is cost-effective and has proven to be cheaper compared to the conventional sensor. Moreover, the system only uses a single wireless module with temperature, light, and CO^2 sensors but is capable of detecting temperature, carbon dioxide, room occupancy, lighting, and fire detection and is 33% cheaper than traditional sensing solutions.

To confine the definition of smart automation for indoor fire to just automated sensors or early fire detection would be narrow and not encompass the entire knowledge base relating to fire detection. As demonstrated in [45], this definition can encompass a broad range of subsets. Researchers have developed an approach to simplify the complex process of integrating sensor data with BIM, showcasing the diverse ways in which smart automation can be applied to fire detection. Known as building information modelling language (BIMSL), it addresses the process's complexity due to the growth of interest in associating sensors with BIM for better visualisation. Instead of the usual general purpose language (GPL) method to link sensors and BIM, [45] is developing its BIMSL using domain-specific language.

Collectively, these previous studies outline the critical role of data, be it real-time or in the past, which can help ensure smart automation is successful. Real-time data could improve and accommodate real-time incidents, while historical data could train a model to forecast an incident intelligently. On that account, the terms commonly correlated with data in smart automation are data mining and big data. For example, in Lisbon, [46] uses a data mining approach to identify the most exposed area and forecast future incidents to improve the quality of life for its residents. The datasets from past events containing building fires and other incidents from 2011 to 2018 underwent the cross-industry standard process for data mining (CRISP-DM). An abundance of big data sources, including both structured data such as casualty reports and demographics, and unstructured data such as crowdsourcing and social media, hold significant value for disaster management. However, to harness their full potential, further data harvesting, aggregation, and pre-processing are necessary. In response, [47] put forward a novel architecture that integrates the Hadoop ecosystem and Apache Spark engine to analyse this information in support of Disaster-Resilient Smart Cities (DRSC). This logical analysis contributes to disaster management applications, providing a more comprehensive understanding of the data and its implications.

3.3. Evacuation and indoor navigation

During indoor fire hazards, safe evacuation with limited perception of the route and navigating in limited visibility is challenging. To ensure safety, numerous researchers have explored the topic of safe evacuation and navigation, with a vast amount of literature and findings already proposed. This topic has gained interest since the earliest timelines and is evergreen. However, the incorporation of information technology-related and smart capabilities dates back to at least 2012, when [48] combined information and communication technologies (ICT) and mobile applications to provide evacuation paths and other solutions. The evacuation route is customised according to the user and can provide multiple viewing solutions, such as in 3D format. Identifying trapped occupants is the most challenging task for first-line firefighters. However, recent research [49] has continuously identified a method to localise trapped occupants using inertial sensors. The model will receive a verbal alert from the occupants that will be translated using natural learning understanding (NLU) and will track the movement dynamically using several equations combined with the coordinate system and occupants' stride. Previously, due to technological limitations at that time, locating trapped evacuees could be time-consuming. In [50], angle of arrival estimation was used for a localisation algorithm that provides continuous monitoring for safe building environments. Meanwhile, [51] uses RFID to pinpoint indoor locations, enabling safe evacuation through the use of WSN and mobile applications that include arrow signs for navigation. These innovative approaches demonstrate promising potential for enhancing the safety and security of indoor environments during emergency situations.

During indoor emergency evacuations, time is of the essence for both evacuees and rescuers, who often prioritise the shortest path to safety. Based on a literature review, it appears that the Dijkstra algorithm is increasingly being recognised as a viable solution for optimising evacuation routes. Several studies, including [27,41,49,52–54] have incorporated the Dijkstra algorithm in their research, with personalisation to accommodate the aim and objective of the research.

While [52] was concerned with providing clog-free and shortest-safety path navigation (ECSSN) for trapped occupants, [27] was more concerned with providing optimal and real-time path guidance for fire-fighters during search and rescue. The ECSSN with the IoT-WSN method is constructed based on the concept that trapped occupants far from the dangerous area will have a clearer and shortest path to exit. Contrary to the trapped occupants near the dangerous area, they are prone to congestion and will have difficulty looking for a way out [52]. Dijkstra's algorithm is used in [27] to compute a navigational route to provide fire-fighters with an optimal rescue path while taking into account all factors, such as the minimum pace obligation in fire rescue or the indoor building conditions. Unlike [53], most researchers focus on a small area to validate their respective systems or methods due to the network's complexity in determining the starting or ending point, particularly during emergencies. However, in order to prove the effectiveness of the proposed smart exit sign for real-time fire incidents, [53] corroborated and assessed the developed automated direction setting algorithm (ADSA) aligned with other algorithms based on a scenario with different building capacities and ADSA could provide the crucial information of exit signs in less than three seconds even with 1500 nodes as input.

Meanwhile, [54] focused on providing the safest path, not necessarily the shortest, using its customised algorithm and communication protocol. The proposed system was validated using a distributed building evacuation simulator (DBES) with different scenarios. The outcome shows that the system could assist in the evacuation and simultaneously ensure the evacuees maintain their health despite the fire incident. Interestingly, [49] has developed a pathfinding module between trapped occupants and fire-fighters using voice commands. When the occupants use the mobile app to enter their voice command with sufficient information (room number and level), the system will provide the firefighter with the shortest navigation path based on Dijkstra to the trapped occupants. Finally, [41] used the Dijkstra algorithm for both of its modules to help trapped evacuees navigate their way out and assist fire-fighters to help locate trapped occupants. The only difference is that the former uses a penalty factor in its calculation to avoid navigation results toward the fire region, while the latter does not employ the penalty factor.

In addition to utilising the Dijkstra algorithm, researchers have also explored the potential of sensor node networks to enhance safe indoor navigation during emergency situations. One study, [55] which focused on WSN and the importance of available egress duration (AED) in dynamic fire scenarios, proposed a fast fire escaping algorithm (SEE) and evaluated its performance against two benchmark algorithms (PRE and GLOBAL). The study used TelosB to validate the system, and the results indicated that SEE produced a more dependable maximum safe egress time (MSET) than the other two algorithms.. Likewise, [56] builds a sensor network using TelosB to create its WSN, and if the sensor detects any reading that surpasses its designated limit, the nodes will adjust the direction and provide safe exit navigation. Another example of the implementation of WSN is highlighted in [57], where it integrates a light resistor sensor, Arduino-Uno, and wireless communication module and presents a smart exit sign system (SISES). [57] SISES focused on establishing communication between the controller without a central server but by depending on WSN. As a result, the stability and reliability of the established communication protocol are reported to be less than four seconds despite the condition of the building (obstruction, multi-level).

Apart from emphasising finding the shortest path, a few researchers have drawn on various attributes related to safe fire evacuation. A concept based on augmented reality (AR) for evacuation and real-time monitoring using various IoT sensors such as flame, smoke, and multi-gas detectors was proposed by [58], which also incorporated a smart fire extinguisher element. The AR was developed using the Unity engine, and occupants and rescuers could access the AR information via mobile phones. A study also focuses on determining dynamic exit signs using BIM as an input to the algorithm. Specifically, using a navigation graph network extracted from BIM, the research tried to generate an optimal route to the exit signs and discover the negated directions [59]. Similar to the approach taken in [59,60] included the smart exit signs component in their research on top of providing an evacuation route to the occupants using the A* algorithm. Bluetooth low energy beacons (BLE) were used for sensing and localization, and the ESP32/MQ-2 was used for sensing. In contrast to previous studies that focus on the perspectives of building occupants or both occupants and rescuers, another study examines the viewpoints of firefighters specifically. This research aims to support firefighters during emergency situations by establishing a temporal mobile weighted graph (TMWG) that integrates navigational, risk prediction, and steady communication modules [61]. To achieve this, the study employs a wireless body area network (WBAN) that the firefighter carries, which dynamically compiles information on the firefighter's condition and real-time situation. An interesting approach focusing on the correlation of body mass index (BMI) with ascending evacuation speed using stairways revolves around mathematical equations and developing intelligent devices [62]. The idea starts with the hypothesis that ascending evacuation speed and time correspond with the evacuee's BMI, and an experiment was conducted to prove the hypothesis. The experiment validated the hypothesis, and to improve evacuation efficiency, a smart safety design for fire stairways was proposed incorporating the weight sensor, height ultrasonic detector, central processing device, and pedestrian identification device without having to modify the stair architectural characteristics.

Ultimately, the use of AI for evacuation purposes is also available, as discussed by [26,28,63]. [26] used a different approach in generating the path planning, which features a back propagation (BP) neural network and available local egress time (ALET) as the input for the time factor in the designated algorithm. The trained BP neural network is adapted to expedite the path-planning procedure. On the other hand, sensor information (temperature, fire growth rate, carbon monoxide concentration) and individual factors (physical and non-physical) were used as the input information for an artificial neural network (ANN) to provide dynamic routing and navigation for evacuees [28]. The model in SmartEscape reads the input as a risk score, eliminates the possible threat, and intelligently provides the routing according to the real-time indoor building environment and evacuees' physical attributes [28]. Finally, a trained support vector machine (SVM) is used to examine and classify historical sensing information recorded via the Raspberry Pi 3 model with a camera as hazardous or non-hazardous [63]. Also, it uses cloud computing, which employs the A* algorithm for the evacuation element.

3.4. Early fire detection, intervention, and prevention

Technological advancements have led to many innovative inventions, including in the field of indoor fire safety. Researchers have proposed various methods for detecting early fire signs, intervening, and preventing further spread. Moreover, during the early inception of the Internet of Things (IoT) and the Web of Things (WoT), a study focused on incorporating these technologies with virtual objects (ViO) and context awareness to establish a comprehensive fire management system. This system includes an archived log repository in the form of semantic ViO and can detect fires and assist in making real-time decisions based on current information [64]. Another ICT-orientated research project known as CAP-ONES, crafted on the previous work of SEcure Message Accessibility for All (SEMA4A) ontology from other research, sends an emergency alert in a common alerting protocol (CAP) in the forms of description, danger level, video, image, and others [48]. Both studies incorporated cutting-edge technologies and unique concepts of that era to develop a single, all-inclusive system. The integration, interoperability, and harmonization of each concept were complex and time-consuming, but the end result was a comprehensive system. As time has progressed, advancements in technology have made the process simpler and more manageable.

Diverse concepts were continuously introduced, such as integrating IoT and blockchain [65], automated fire-fighter prototype robots to prevent fire spreads [66], and smart "e-nose" for hazardous gas detection [67]. The idea of [65] is focused on detecting fire in the kitchen by developing a device installed in the stove's outlet that can function in online and offline modes. The device is built using ESP8266MOD, integrating Ethereum hosted by Infura and Firebase to push communication via mobile apps. A prototype automated firefighter robot has been developed using ESP for WiFi communication, as reported in a study [66]. The robot is built using an Arduino Mega and a flame sensor, and the ESP 8266 enables it to detect and extinguish fire autonomously. As for [67], it paired an Arduino with multiple gas sensors and trained it with AI to find the highest sensitivity gas sensor, which is the TGS2600, using SVM. Likewise, [68] focuses the research on detecting hazardous gases such as carbon monoxide, liquefied petroleum gas (LPG), and hydrogen sulphide using Arduino Uno, multiple gas sensors, and its distinctive feature of using solar power as the power source. Meanwhile, to improve the reliability and accuracy of data from various sensors installed on the waspmote controller, [69] uses fuzzy logic to create fire probability values. Similar to other sensor concepts, the sensor could detect early signs of fire, and using the fuzzy logic method, the transmission of data packets will be more frequent than usual.

Although false alarms are inevitable despite the various types of technology and concepts proposed, there are ways to reduce their occurrence. Some ways can be implemented to reduce the false alarm rate. Using AI in early fire detection could significantly reduce the potential for false alarms. Several researchers have discussed the potential of using AI embedded in their systems. For example, [70][proposed a multi-sensor system that uses an Arduino Uno as a microcontroller and has performed classification to conclude that SVM can produce accurate fire detection performance.

On the other hand, [71] employed LSTM, a type of CNN, for temporal data prediction. The method cannot only predict but also specifically identify the source of fire, as it is trained with 100-tunnel fire scenarios with 94% prediction accuracy. A system known as HelpResponder is composed of the IoT-BLE protocol for sensing purposes and has a thermal camera embedded with an artificial vision algorithm to forecast early fire signs [72]. To substantiate the efficiency of the concept, a simulation was carried out. The results show that using the system, a fire-fighter could arrive at the fire scene six minutes earlier than without the system. Instead of using an image to predict early fire signs, [37] uses the same approach as [68], which uses real-time information fed by the multiple sensors and customises a fire detection algorithm based on weighted dynamic time warping (WDTW). The similarity match between the sensor's signal structure can be used as an equation to predict fire [37]. The research presented in [46] utilised an AI algorithm to analyse historical incident data related to risks in Lisbon, with the aim of anticipating and addressing the city's recurring incidents. The study employed two datasets and four classification algorithms (logistic regression, k-nearest neighbours, SVM, naïve Bayes, decision tree, and random forest). The findings suggest that predicting fire and industrial-technological accidents is challenging and requires additional information

3.5. BIM related

According to the final findings from the literature search, it was revealed that the incorporation of BIM in research began in 2014. Since then, an increasing number of researchers have emphasised BIM in their studies, with the most recent study including BIM in 2022. This transition in BIM's role can be summarised as evolving from a supportive element in research to a central focus of the study.. In 2014, [42] developed an algorithm that uses geometric information extracted from BIM of the sensing area as a visual reference for interaction between firefighter and fire incident commanders. The use of BIM in this research is to improve the quality of space segregation and could reduce false room level localisation.

As the integration of BIM and digital sensors grows, integrating BIM and real-time sensors is becoming more difficult due to a lack of interoperability software and limited BIM knowledge. Therefore, [45] took the initiative in 2017 to propose a generic approach to integrate BIM and real-time sensor information by leveraging Domain-Specific Language, a state-of-the-art software engineering method. Known as building information modelling language (BIMSL), it was developed in five stages and evaluated by applying the Modbus data communication protocol and hands-on usage by professional software engineers.

Subsequently, the implementation of BIM as a visual aid was emphasised in studies by [27,41,59,73]. amongst these, [41] introduced a fire prevention system for smart buildings, using Autodesk Revit to construct a BIM model that comprises five distinct modules. These modules were divided into several databases and were integrated using the Revit API. Furthermore, the BIM model illustrated the implementation of Bluetooth sensor networks, with the readings transmitted using the Raspberry Pi 3. Operating on the equal BIM-based software, [59] automatically determines exit sign direction, recommends direction to the exit based on the shortest accessible evacuation route, and calculates negated directions corresponding to hazardous areas. Using Autodesk Revit to construct its BIM model, the study uses a navigation graph network as the input to the algorithm that required the generation of floor navigation path lines and stair path lines. Using different theories and concepts, [71] tried to link fire incident information with a visualisation platform using lightweight communications and marshalling (LCM), a computational framework. In their study, [73] developed a WSN simulator that enables individual sensors to publish LCM data packets to a central monitoring hub, which then communicates with its event detection model. The resulting event detection was subsequently visualised in BIM using AECOsim Building Designer (ABD) as a post-processing feature rather than in real-time. Notably, each event was classified according to the level of threat and was represented using different colors. On the contrary, [27] focused on visualising real-time incidents and providing a dynamic route to the first responder. In the BIM model, the fire incident commander can view the number of Bluetooth sensors deployed in the building, while fire rescue route planning can be accessed through the integration of the BIM model and SQL server.

Meanwhile, focusing on the industry foundation classes (IFC)-BIM relationship[5] [26] furnished a rescue route constructed using geometry network model (GNM) through IFC models. The IFC class/relations extraction was executed using the IFC JAVA TOOLBOX toolkit, and subsequently, the relationship between the elements was adopted to create topological primitives. In a unique approach, [74] utilised a novel approach to leverage BIM in their study by upgrading existing traditional fire alarm systems to a cloud-based system. The resulting system, called CloudFAS, used BIM to provide a comprehensive 3D visualisation of the building and its fire-related services. The selected building was modelled using Autodesk Revit, with the existing fire alarm system linked to the BIM model using natural language processing. Furthermore, the BIM visualisation platform offers detailed information on the existing sensor, including images and attributes. Instead of installing new digital sensors, the study improves the condition of existing traditional fire sensors through the use of BIM and cloud technology.

3.6. Performance evaluation metrics

Performance evaluation metrics are measures used to evaluate the efficiency, effectiveness, and quality of a system, process, or entity. They provide objective and systematic ways to assess the outcomes, impacts, or results of research findings, experiments, or interventions. These metrics can include various dimensions such as time, accuracy, speed, cost, user satisfaction, or other relevant indicators. Performance metrics are important in evaluating the success or failure of a particular phenomenon or approach, and help establish the validity, reliability, and rigour of a study or analysis. In this review, a table (Table 5) was created to present the performance evaluation metrics of the selected article. The metrics were defined based on the aim, objective, and results of the study. However, for certain articles, the performance evaluation metrics could not be established or quantified due to the focus only given to the concept and some of the claim e.g., of the proposed system being cost-effective, without providing solid references to support the statement. Additionally, some articles were focused on the implementation of the concept, with limited elaboration on the results. Table 5 provides a comprehensive representation of the performance evaluation metrics used in the research, and their definitions are as follows:

- Accuracy/Precision: The metric measures the correctness or exactness of the results or outputs produced by a system or process. It reflects the degree to which the outcomes align with the expected or desired outcomes, and is often expressed as a percentage or a ratio. High accuracy/precision indicates a low level of errors or inaccuracies in the results, while low accuracy/precision may indicate a higher likelihood of errors or inaccuracies.
- Sensitivity: This metric measures the ability of the sensor system to accurately detect fires and provide timely alerts. A higher sensitivity indicates a more effective fire detection system.
- False positive rate: This metric measures the rate at which the sensor system generates false alarms for non-fire events. A lower false positive rate indicates a more reliable fire detection system with fewer false alarms.
- Response time: This metric measures the time taken by the sensor system to detect a fire and provide an alert. A shorter response time indicates a faster and more responsive fire detection system.
- Scalability: This metric measures the ability of the sensor system to handle increasing numbers of sensors, data points, and devices in a scalable manner. A higher scalability indicates a more robust and adaptable fire detection system.
- Robustness: This metric measures the resilience of the sensor system to environmental factors such as temperature, humidity, and smoke, as well as system failures. A more robust system can continue to function effectively even in challenging conditions.
- Energy efficiency: This metric measures the power consumption of the sensor system, including the sensors, communication modules, and processing units. A more energy-efficient system can prolong the battery life of the sensors and reduce overall energy consumption.
- Cost-effectiveness: This metric measures the cost-effectiveness of the sensor system, including the cost of sensors, communication modules, installation, and maintenance. A more cost-effective system can provide reliable fire detection capabilities without incurring excessive costs.
- Privacy or security: The metric assesses the level of protection or confidentiality of sensitive data or information within a system or process. It reflects the effectiveness of measures or controls implemented to safeguard data from unauthorized access, disclosure, or breaches. High privacy/security indicates a robust level of protection, while low privacy/security may indicate vulnerabilities or risks of data exposure or unauthorized access.

3.7. Common technical jargon

Upon a closer examination of these articles, it becomes evident that there is a commonality in the usage of technical jargon and technology usage across the research, specifically in the field of IoT sensors and smart buildings. This recurring technical jargon, which is apparent in the articles under scrutiny, is likely influenced by the specific objectives and aims of the research studies. To provide a comprehensive overview of these technical terms, a list of related jargon is provided in Table 6.

[5] IFC is a file format used in BIM that enables different software applications used in the construction industry to exchange data more easily. It serves as a universal language for BIM data exchange, allowing for better interoperability between different systems.

Table 6
Recurring technical jargon in the articles.

Common technical jargon	Terms and related articles
IoT-WSN	NodeMCU [25,31,32,34,36,52,60,65,66]
	Xbee [69]
	ZigBee [38,58]
	BLE [27,41,43,60,72]
Microcontroller	Arduino [31,32,40,57,63,66–68,70,72]
Sensor	MQ-2 [25,34,36,40,52,60,70]
	LM35 [38,40,52]
	PIR [36,39,40,52,68]
Raspberry	Raspberry Pi [60]
	Raspberry Pi GPIO [43]
	Raspberry Pi 3 [25,63,72]
	Raspberry Pi 4 [34]
AI and Deep Learning	Fuzzy Logic [25,69]
	Nearest neighbour (NN) [37]
	K Nearest neighbour (KNN) [46,67]
	ANN [28]
	CNN [23,24,26]
	NLP [74]
	NLU [49]
	RNN [30]
	SVM [46,63,67,70]
	Random Forest [46,70]
	BP Neural Network [26]
Path Algorithm	Dijkstra Algorithm [27,35,41,49,52–54,59]
	A* [60,63]
BIM	Autodesk Revit [27,41,59,74]
	ABD [73]
	IFC [26,45,49]
Fire Simulation	FDS [47,55]
Localisation	RFID [28,51,61]

3.8. *Additional findings*

Another significant finding in the review is that the majority of the studies reviewed focused on the basic functionality of sensors such as detecting the presence of smoke and flame, as well as changes in temperature and humidity levels in the building. The research falls short in identifying potential fire hazards caused by electrical sources. Additionally, most of the studies emphasised determining the shortest path to safety during emergency fire hazards. To ensure a safe and efficient evacuation, it is essential to consider both the occupant and rescuer perspectives. Furthermore, the review highlights an increasing trend towards incorporating Building Information Modelling (BIM) in smart building systems, as it provides a powerful tool for visualising the building's layout and structure. During indoor hazards, access to BIM can provide occupants and rescuers with clear directions, thereby enhancing safety during emergencies.

4. Discussion

Upon synthesising the 54 articles, it is apparent that the utilisation of IoT sensors in smart buildings for indoor fire hazard prevention is vast and multifaceted, encompassing diverse ideas, concepts, and technological applications. Deriving from thematic analysis of selected articles this review has developed five themes and 24 sub-themes. The researchers have sought to establish the advantages of using IoT sensors for indoor fire hazards according to the identified themes: vision-based sensing, smart automation, evacuation and indoor navigation, early fire detection, intervention, and prevention and BIM-related.

The increasing popularity of vision-based sensing as a supplementary technology to IoT-based sensors in recent years has been accompanied by growing recognition of its limitations, particularly in terms of the inability of traditional cameras like CCTV to detect and respond to potential threats without human intervention. However, the implementation of AI and deep learning algorithms has significantly improved the reliability and effectiveness of vision-based sensing, as evidenced by the findings of recent studies such as those reported in [23,24]. By incorporating deep learning cameras or glasses equipped with a visual aid feature, early signs of fire can be detected, and threats can be predicted automatically, providing significant benefits to various stakeholders such as individuals with vision impairments, fire authorities, and building owners. Notably, the use of AI and deep learning algorithms in sensing systems is an area of growing interest and has been the subject of numerous research studies, including a systematic review conducted by [75] which focused on artificial intelligence-assisted techniques for building control systems. While this review was primarily concerned with thermal comfort and energy efficiency, it also highlighted the potential of AI, deep learning, and machine learning tools and concepts for enhancing the effectiveness of sensing systems in a range of applications. Overall, the integration of AI and deep learning algorithms in vision-based sensing systems has significantly enhanced their performance and has the potential to revolutionise the way in which various stakeholders approach the detection and management of potential threats. Ongoing research in this area is likely to yield further insights into the capabilities and limitations of these technologies and their potential for a wide range of applications.

The findings from this research also highlight the fact that relying on sensing technology alone is inadequate for constructing an effective and reliable smart building system. To address this issue, it is necessary to integrate sensing modules with other components and modules to create a complete and robust system. The ideal smart building system should be composed of four layers of components, namely, sensor, communication, evacuation, and visualisation, each of which performs a specific function that contributes to the overall efficacy and reliability of the system.

The sensor layer of the smart building system is responsible for collecting data from various sensors, such as temperature, humidity, motion, and gas sensors, and transmitting the data to the communication layer. The communication layer facilitates the transfer of data between different layers and components of the system, including the sensors, evacuation systems, and visualisation tools. The evacuation layer is responsible for alerting building occupants of potential threats or dangers and guiding them to safety in the event of an emergency. Finally, the visualisation layer provides real-time data visualisation and analysis to enable building managers and stakeholders to make informed decisions about the operation and maintenance of the building.

Several research studies have demonstrated the effectiveness of smart building systems that incorporate all four layers of components such as sensors, communication, visualisation and evacuation including those conducted by [28,30,58]. Such systems have been shown to significantly enhance building safety and efficiency. It could be deduced that while sensing technology is a crucial component of smart building systems, it is important to recognise that it must be integrated with other modules and components to create a complete and effective system. A smart building system that includes all four layers of components has the potential to significantly enhance building safety, efficiency, and occupant comfort.

Sensing technology forms the core of smart building systems, and many researchers have utilised customised IoT-WSN-based sensors built with BLE, NodeMCU, Raspberry Pi, or Arduino to collect data [27,31,32,34,40,63]. These sensors are highly accessible and customisable to suit the research scope. However, finding from this research indicated that most of the IoT-based sensor research has only focused on basic environmental sensing parameters such as temperature, humidity, smoke, and flame. Nevertheless, some researchers have explored additional fire-related parameters, such as detecting the presence of LPG, as demonstrated by [25,34,68]. Since LPG is a flammable substance classified as a hazardous substance and can undergo a boiling liquid expanding vapour explosion when subjected to fire, detecting its presence is important. Moreover, some researchers have incorporated passive infrared (PIR) sensors for human detection to identify the number of building occupants [36,39,40]. While this additional sensing information can be useful, it can also lead to false movements and misinterpretations. Hence, it is deemed essential to integrate additional sensing technologies, such as deep learning and vision-based sensing, for further verification and comprehensive observation. Although customised IoT-WSN-based sensors are widely used in smart building research, there is a need to focus on additional fire-related parameters and integrate advanced sensing technologies such as vision-based sensing and deep learning for accurate and comprehensive data analysis.

The evacuation route and navigation are crucial elements in ensuring the safety of occupants during a fire incident. While most research in this area has focused on finding the shortest path, as evidenced by [49,52–54] that have adopted the Dijkstra algorithm, it is important to note that the shortest path is not necessarily the safest one. To ensure a smooth and reliable egress path, the algorithm should exclude unsafe paths from consideration. Effective communication between trapped evacuees and fire-fighters, as well as between fire-fighters and the fire commander, is critical during emergency fire incidents. The communication medium must be stable and consistent, without any latency, and the location of both occupants and fire-fighters must be accurately determined. While several localisation methods have been proposed by [28,51,61], it is imperative to find the most stable and accurate method to determine the exact location of occupants and hazards. Moreover, the incorporation of additional visualization elements in the system can significantly assist the communication and search and rescue (SAR) procedure. A clear picture of the affected area from both the occupant's [28,41] and the fire-fighter's points of view [27,42] can increase the rescue response rate and decrease the rescue time. Future research in this area should consider expanding the visualisation component for both the occupant and rescuer points of view, which would enhance situational awareness and improve rescue operations.

While the demand for a smart building is expanding and BIM is commonly associated with establishing the smart building concept, it is important to completely grasp the concepts of IFC and BIM as both terms are interchangeable. BIM is a visualisation platform due to its ability to connect with IoT-WSN sensors. The information can be visualised in a 3D model with complete information using the proper tools. However, it is indisputably that integrating the IoT-WSN sensor into the BIM platform can be challenging. This is highlighted in [45], motivating the researcher to propose its BIM translator. The major drawback regarding smart buildings and BIM is the data interoperability issues. More and more research has explored this theme with the incorporation of geospatial-based software. However, a comprehensive overview is required so that it can assist both technical and non-technical smart building and BIM users.

Besides focusing on the core research question that becomes the pillar in constructing this review, this research has also discovered technology and applications commonly associated with IoT sensors, indoor fire hazards and smart buildings. The recurrence of these technical terminologies in the examined articles shows that these technologies are imperative in establishing an IoT sensor in the smart building environment, particularly in tackling indoor fire hazards. As an example, a study conducted on IoT sensors in smart buildings for indoor fire hazard prevention might employ Dijkstra's algorithm to navigate occupants to safety through the shortest and clog-free path. On the other hand, another research might focus on providing optimal and real-time path guidance for firefighters during search and rescue operations in the event of a fire. These distinct approaches demonstrate the versatility of IoT sensors and smart buildings in addressing indoor fire hazards. Each study employs the same fundamental concepts but applies them uniquely based on the specific aims and objectives of the research. By exploring these diverse technical applications, researchers can gain a better understanding of the potential of IoT sensors and smart buildings in mitigating indoor fire hazards. These findings provide a valuable insight for future research. It is suggested that it is best to consider including these technologies in any potential system proposal to ensure its reliability, efficiency and relevancy.

5. Future research directions

5.1. Exploring tailored approaches for other hazardous environments

This study specifically focuses on the indoor fire hazards that arise in smart building environments. However, it is important to note

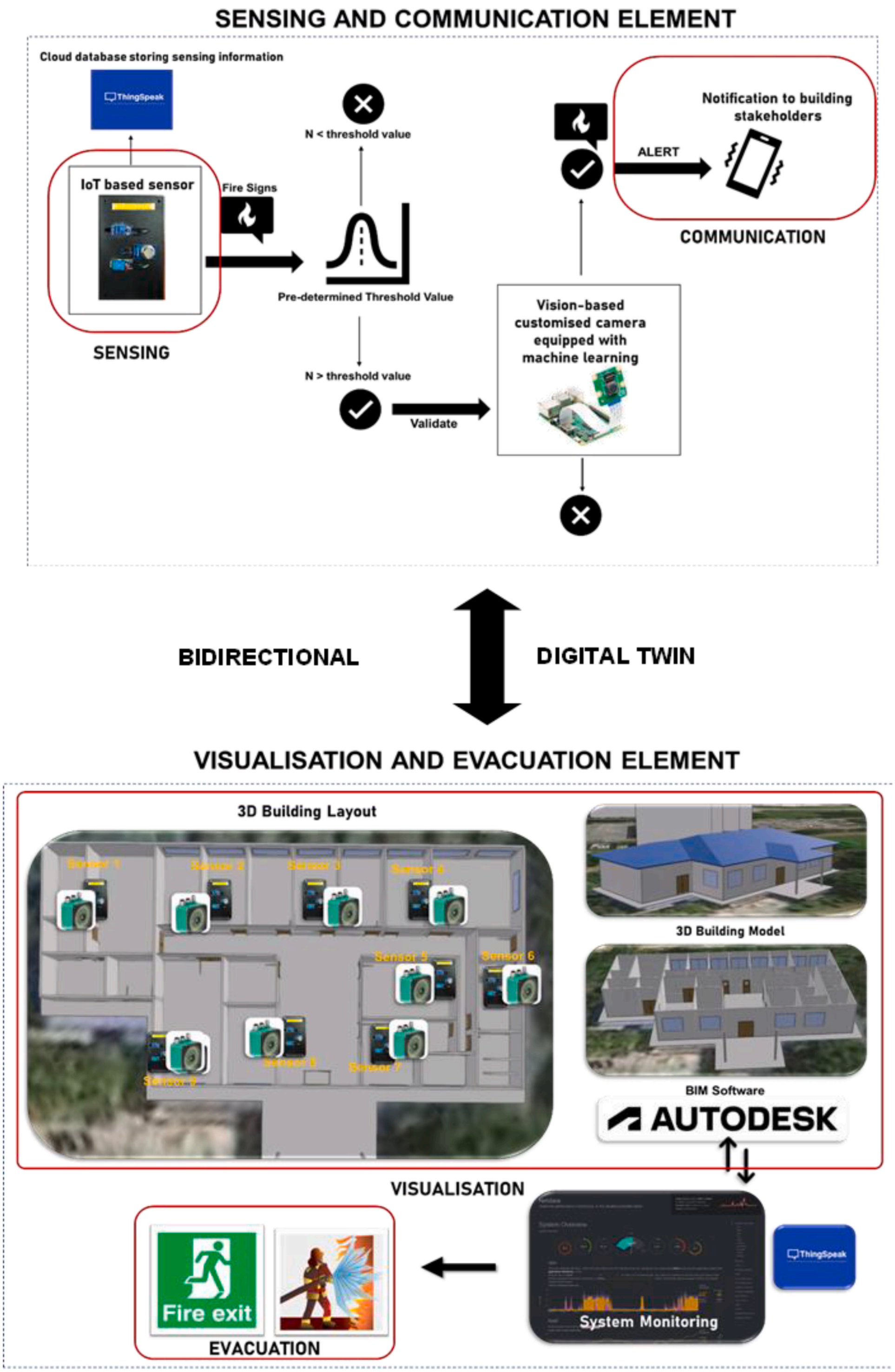

Fig. 6. A proposed conceptual framework for IoT sensors in a smart building context.

that there are other areas of concern that require tailored approaches due to their unique characteristics, such as confined spaces like tunnels and mines, or outdoor settings like forests. For example, tunnels may not conform to standard shape and size assumptions, and user interface information must be adaptable to meet specific local department requirements. Therefore, it is necessary to explore and address similar problems in other areas that pose a risk of fire.

Several recent studies have explored fire detection and mitigation in different locations. For instance, [76] uses collocated commodity speaker and microphone pairs to detect fire inaudibly, while [77] employs an IoT stack platform, cloud server, and data analytics to detect, predict, and monitor the danger of fire in real-time in coal mines. Detecting and mitigating forest fires also requires specific approaches. The research by [78] proposes an IoT and YOLOv5 based solution for early detection and classification of fires in forests, while [79] presents a Video Surveillance Unit (VSU) that uses machine learning algorithms to detect forest fires through audio and visual inputs. Future research can focus on developing tailored approaches for these specific environments, taking into consideration their unique characteristics and requirements, and the use of machine learning algorithms for fire detection.

5.2. Addressing fire caused by chemical and electrical factors

Additionally, the insufficient emphasis on addressing fires caused by chemical and electrical factors constitutes a significant issue that demands attention. Presently, the detection of LPG (liquefied petroleum gas) presence has been the primary focus of only a limited number of studies [25,34,68]. As such, it is imperative to consider the capabilities of sensors that can effectively detect fires associated with chemical and electrical factors. For instance, the use of MQ-135 sensor can be explored for chemical fire detection, while a current transformer (CT) sensor may be suitable for electrical fire detection.

5.3. Integration with emergency response systems

Integration with emergency response systems is a crucial aspect of research on IoT sensor-based indoor fire hazard detection. Exploring how these systems can be seamlessly integrated with existing emergency response systems, such as fire alarms, sprinklers, or emergency notification systems, can enable a comprehensive and coordinated response to indoor fire hazards. For example, when a fire is detected by the IoT sensors, the system can automatically trigger fire alarms, activate sprinklers, and send notifications to emergency responders or building occupants. This integration can enhance the overall effectiveness of fire detection and mitigation measures, enabling faster response times, coordinated actions, and better management of fire incidents. Furthermore, exploring interoperability and communication protocols between IoT sensor-based fire detection systems and existing emergency response systems can ensure seamless integration, compatibility, and efficient information exchange, leading to more effective and coordinated emergency response in case of a fire hazard.

5.4. Long-term maintenance and system robustness

Long-term maintenance and system robustness are critical areas to venture. Examining the sustained performance and reliability of these systems over an extended period of time, including potential challenges related to sensor degradation, sensor drift, and overall system robustness, is essential for ensuring the longevity and effectiveness of the fire detection system. Gaining a comprehensive understanding of the potential issues that may arise over time, such as degradation or drift in sensor performance, can inform the development of strategies for system maintenance, calibration, and sensor replacement, thereby ensuring continuous and reliable detection of fire hazards. Addressing the challenges associated with long-term maintenance and system robustness is crucial to ensure that IoT sensor-based fire detection systems remain accurate, reliable, and efficient throughout their operational lifespan. This may involve regular monitoring of sensor performance, periodic calibration, and replacement of sensors as needed, as well as the development of mechanisms to detect and handle potential system failures or errors. Proactively addressing long-term maintenance and system robustness concerns can help researchers and practitioners ensure that IoT sensor-based fire detection systems remain effective and reliable for long-term deployment in indoor environments.

5.5. Proposed conceptual framework

Based on the exploration of possible methods and concepts used in similar problem areas, as well as the findings from the thematic literature search, this review proposes a future direction by establishing a conceptual framework corresponding to the findings, as shown in Fig. 6.

Overall, the proposed conceptual framework represents an ideal system that incorporates various elements of sensors, communication, visualisation, and evacuation to enhance fire safety in buildings. The proposed idea revolves around the development of an Internet of Things (IoT) based sensor, which is built using the cost-effective ESP 8266 microcontroller and a variety of sensors. The sensors used include MQ-2 for smoke detection, DHT 11 for temperature and humidity detection, and a flame sensor for early fire detection. In addition, the MQ-135 sensor is used to detect chemical fires, as it is capable of detecting a range of gases including smoke, benzene, alcohol, CO_2, ammonia, and other harmful gases commonly associated with chemical fires. To detect electrical fires, a current transformer (CT) sensor is employed, which measures the current flowing through a wire and can detect changes in the electrical current caused by arcing or other abnormalities that may indicate an electrical fire. Both sensors can be easily integrated into IoT-based systems for remote monitoring and data analysis.

Installation of the plural based sensor is easy as it is wireless and does not require any tampering with the existing building. In addition, the incorporation of a buzzer or flasher can serve as a notification mechanism to cater to individuals with visual or hearing impairments, enhancing the inclusivity and accessibility of the IoT sensor-based fire detection system. The data collected by the various sensors are stored in an accessible cloud database known as ThingSpeak, which also functions as a sensor monitoring hub. By linking the IoT sensor to a database, the sensor information can be used for various purposes, such as machine learning. One possible machine learning algorithm that can be used is the SVM algorithm. SVM is a popular algorithm for classification tasks and has been successfully used in various applications, including fire detection. The collected data from the sensors can be used to train the SVM algorithm and can be employed to classify the detected fire and gases into different categories. Additionally, the dataset can be used for advanced analysis using geospatial information system software to understand the analytic pattern further.

To trigger real-time notification, a messaging application can be configured to actuate transmission of a fire emergency event alert upon determination of a fire hazard. Specifically, the flow starts when the sensor detects any early signs of fire in the building, and the sound from the buzzer and indicator from the flasher will indicate a probable fire incident. The IoT sensor will be predetermined with a logical threshold value, and if the value is less than the predetermined value, it signifies a false alarm. However, if the sensing value exceeds the predetermined value, it suggests a possible fire incident. The customised vision-based camera with deep learning will then determine the integrity of the fire incident to validate the probable fire incident. Following the examination by the vision-based camera, if the fire sign does not conform to the deep learning information, it will lead to a false alarm. If the fire sign is recognised as a fire incident, it will trigger a real-time notification via messaging application to the building stakeholders for the next course of action.

Furthermore, the installed IoT-based sensor inside the building can be visualised in the BIM platform. This platform can benefit building stakeholders, fire-fighters, or building safety officers for advance monitoring and evacuation purposes. The real-time incident that happened indoors can be dynamically visualised using BIM, which aligns with the digital twin concept. A digital twin is a compilation of the surrounding environment and simulation of the proposed system that represents real-time, can forecast future conditions, and simultaneously assists in improving decision-making [80]. Although minimal reference can be found regarding the digital twin in the selected articles, [30] did incorporate the digital twin concept in the proposed intelligent system, while [58] intended to realise the digital twin concept for future research. Moreover, a recent systematic review by [81] also features themes regarding smart cities and digital twins, as both are strongly affiliated. The review examined the probability of connecting digital twins and smart cities for indoor.

6. Conclusions

The present study systematically reviewed the application of IoT sensors in the event of indoor fire hazards in a smart building context based on the 54 selected articles. From the review, it is evident that integrating IoT sensors with other state-of-the-art technology, such as AI, deep learning, and BIM, can offer several advantages in many aspects of indoor fire hazards. Building owners, building administration and security, the fire department, and researchers can gain valuable insights into the sophisticated technology that could assist in enhancing the safety of smart buildings.

The review highlights that IoT sensors could enhance indoor fire hazard incidents before, during, and after. By embedding AI and deep learning in the system, fire signs could be detected early, and early intervention could reduce the risk of more extensive fire occurrences. Moreover, reliable and accurate evacuation and navigation routes to the exit during fire incidents could significantly assist trapped evacuees in egressing safely. Firefighters could also benefit from supplementary information like real-time navigation, visualisation, and intelligent fire extinguishers, which could significantly improve the search and rescue process and reduce the standard safe time benchmark. The sensing information stored in the database can also be used for transfer learning to enhance the sensing capabilities, making the authentication process of fire detection using IoT or vision-based sensors more reliable and trustworthy.

This research has established that there are numerous research opportunities to venture into embedding IoT sensors to establish a smart building that could cater to indoor fire hazard incidents. In the future, further studies could explore the effectiveness of integrating IoT sensors with other emerging technologies, such as the use of acoustic sensor, blockchain and AI. In addition, expanding the capabilities of sensors to detect various types of fires, such as electrical and chemical fires, could further enhance the efficiency and safety of fire hazard management solutions. Overall, IoT sensors' incorporation in smart buildings is a promising approach to mitigating indoor fire hazards and ensuring occupant safety.

Data availability

No data was used for the research described in the article.

CRediT authorship contribution statement

Sarah Shaharuddin: Writing – original draft, Writing – review & editing, Conceptualization. **Khairul Nizam Abdul Maulud:** Writing – review & editing, Supervision, Conceptualization. **Syed Ahmad Fadhli Syed Abdul Rahman:** Writing – review & editing, Conceptualization. **Adi Irfan Che Ani:** Writing – review & editing, Supervision. **Biswajeet Pradhan:** Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Khairul Nizam Abdul Maulud reports financial support was provided by Universiti Kebangsaan Malaysia Faculty of Engineering and Built Environment.

Data availability

Data will be made available on request.

Acknowledgement

The author would like to thank Universiti Kebangsaan Malaysia (UKM) for the Perdana Impact Fund research grant (DIP-2021-006) and Earth Observation Centre for the technical support.

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