PERFORMANCE EVALUATION OF FIRE DETECTION AND SUPPRESSION SYSTEMS FOR ENHANCING FIRE SAFETY IN HIGH-RISE BUILDINGS

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ABSTRACT

High-rise buildings present fire safety challenges that differ significantly from low- and mid-rise structures, including extended vertical evacuation distances, stack-effect-driven smoke movement, restricted access for firefighting equipment, and greater consequences of detection or suppression failure. This review paper critically examines the performance of fire detection and suppression systems used in high-rise buildings, drawing on recent empirical, computational and bibliometric studies. The paper synthesizes evidence on conventional detection technologies (smoke, heat and flame detectors), emerging artificial-intelligence-enabled detection approaches, and suppression technologies including automatic sprinklers, standpipe systems, gaseous agents and smoke control measures. Performance evaluation criteria such as response time, detection accuracy, reliability, and evacuation adequacy are discussed, along with the operational, regulatory and infrastructural challenges specific to tall buildings. A comparative summary of key reviewed studies is presented in tabular form to consolidate findings across different geographic and technological contexts. The review concludes that while conventional systems remain the backbone of fire protection in high-rise construction, integration of smart sensing, predictive analytics and improved maintenance regimes offers the most promising pathway toward measurable improvements in life-safety outcomes.

Keywords: Fire detection systems; fire suppression systems; high-rise buildings; fire safety performance; smart fire safety; building evacuation.

1. INTRODUCTION

The rapid vertical growth of cities has made high-rise buildings a defining feature of modern urban landscapes, accommodating residential, commercial and mixed-use functions within a compact footprint [1]. This vertical concentration of occupants, however, introduces fire safety risks that are structurally and operationally distinct from those in conventional low-rise construction. Long travel distances to exit stairs, the unavailability of elevators during a fire event, the stack effect that drives smoke upward through shafts and stairwells, and the physical limitations of external firefighting access all combine to make fire incidents in tall buildings more difficult to detect, contain and suppress within a survivable time window [2].

Historically, fire protection engineering has relied on a layered approach that combines early detection, automatic suppression, compartmentation, and organized evacuation. Detection systems are intended to identify a developing fire at the earliest possible stage, while suppression systems are designed to control or extinguish the fire before it can spread beyond its area of origin. The effectiveness of this layered approach, however, depends heavily on how well individual system components perform under real building conditions, and on how well the systems are inspected, maintained and integrated with one another [3].

Recent bibliometric evidence indicates a marked increase in research attention devoted to fire prevention and mitigation technologies in high-rise buildings over the past decade, with growing emphasis on smart sensing, data-driven analytics and integrated life-safety systems. In parallel, artificial-intelligence-enabled detection and suppression technologies have begun to demonstrate measurable improvements in detection speed and false-alarm reduction relative to conventional equipment [4]. Despite this progress, field evaluations continue to reveal gaps between the fire protection performance assumed at the design stage and the performance delivered during operation, particularly in buildings where inspection and maintenance regimes are inconsistent.

Table 1: Summary of Key Reviewed Studies

Author(s) and Year	Focus of Study	Key Findings / Contribution
Mia, M. M. (2025) [5]	Influence of AI-enabled fire detection and suppression systems on building safety	Shows that AI-enabled sensors, machine-learning based image and smoke analytics, and automated suppression triggers substantially reduce detection latency and false-alarm rates compared with conventional systems, and identifies integration and cost barriers to adoption.
Vovk, Kopchak, Kushnir, Shapovalov & Ferents (2025) [6]	Dynamics of fire development and fire alarm system efficiency in a high-rise building	Models the temporal progression of fire and smoke spread in high-rise floor plans and evaluates how detector placement and response delay affect the efficiency of the alarm system in providing adequate evacuation time.
Kironji, M. (2015) [7]	Evaluation of fire protection systems in commercial high-rise buildings, Nairobi CBD	Field-based evaluation reveals frequent gaps between design provisions and actual operational readiness of detection and suppression equipment, and proposes optimization measures for inspection, maintenance and regulatory enforcement.
Dabous, Shikhli, Shareef, Mushtaha, Obaideen & Alsyouf (2024) [8]	Bibliometric analysis of fire prevention and mitigation technologies in high-rise buildings (2010–2023)	Maps the evolution of research output over 13 years, identifying dominant research clusters (active/passive protection, smart sensing, evacuation modelling) and highlighting an increasing global research focus on smart and integrated fire safety technologies.

The table indicates that fire safety in high-rise buildings depends on technology, proper system design, and maintenance. Mia (2025) highlights the benefits of AI-based systems in improving detection, while Vovk et al. (2025) emphasize the importance of detector placement and response time. Kironji (2015) identifies maintenance and enforcement problems, whereas Dabous et al. (2024) shows a growing shift toward smart and integrated fire safety technologies.

2 FIRE DETECTION SYSTEMS IN HIGH-RISE BUILDINGS

Fire detection systems form the first line of defence in the fire protection hierarchy, as their primary purpose is to identify the presence of fire at the earliest possible stage. Early detection enables timely occupant notification and allows suppression measures to be activated before fire and smoke conditions become life-threatening [9]. This function is especially important in high-rise buildings because occupants may be located many floors above or below the fire source, while smoke can spread rapidly through stairwells, elevator shafts, and other vertical pathways.

Different types of detectors are used according to the characteristics and risks of building areas. Smoke detectors are commonly installed in occupied spaces and circulation areas, while heat detectors are preferred in locations where smoke detectors may produce false alarms, such as kitchens and mechanical rooms. Flame detectors and multi-sensor systems are also used in specific high-risk areas.

In recent years, AI-enabled and smart detection systems have further improved the potential for early fire identification. These systems can analyse sensor, video, and building-management data to recognize fire patterns and reduce false alarms. However, their effectiveness depends on appropriate sensor placement, network reliability, data quality, and integration with existing building systems [10].

2.1 Smoke Detectors

Smoke detectors are one of the most important components of fire detection systems in high-rise buildings because they provide an early indication of fire before temperatures reach the activation level of heat-based devices. Ionization and photoelectric smoke detectors are the two commonly used types. Ionization detectors are generally more responsive to fast-flaming fires that produce relatively small smoke particles, whereas photoelectric detectors are more suitable for detecting slow, smoldering fires that generate larger visible smoke particles. The selection of detector type should therefore consider the expected fire characteristics and the conditions of the protected space [11].

In high-rise buildings, smoke detectors are strategically positioned in corridors, lift lobbies, stairwell entrances, and HVAC return-air ducts. These areas are particularly important because smoke can move rapidly through vertical shafts and circulation spaces, potentially affecting occupants on floors distant from the fire's point of origin. Appropriate detector coverage can therefore improve the speed of alarm activation and provide occupants with additional time to begin evacuation.

2.2 Heat Detectors

Heat detectors provide an additional layer of fire detection and are particularly useful in environments where smoke detectors may be affected by normal activities or environmental conditions. Fixed-temperature detectors activate when a predetermined temperature is reached, while rate-of-rise detectors respond to a rapid increase in temperature. These devices are commonly installed in kitchens, mechanical rooms, and car parks, where dust, fumes, steam, or other conditions may increase the likelihood of unwanted smoke-detector activation.

A major advantage of heat detectors is their greater resistance to nuisance alarms. This can improve the reliability of the alarm system in areas where environmental conditions make smoke detection difficult. However, their relatively slower response means that they may detect a developing fire later than smoke detectors. For this reason, heat detectors are generally not considered suitable as the sole life-safety detection method on occupied high-rise floors. Instead, they are more effective when used as part of a broader detection strategy involving other types of detectors.

The selection and placement of heat detectors should also reflect the characteristics of the protected area. Their use is most appropriate where the expected fire scenario and environmental conditions make temperature-based detection practical. Thus, heat detectors complement smoke detection by providing an alternative means of identifying fire in areas where conventional smoke detection may be less reliable.

2.3 Flame Detectors and Multi-Sensor Systems

Flame detectors are specialized devices designed to detect the infrared (IR) or ultraviolet (UV) radiation generated by flames. Unlike smoke and heat detectors, which identify secondary characteristics of a fire, flame detectors can respond directly to the presence of combustion. Their use in high-rise buildings is generally selective and is particularly relevant to high-hazard locations such as fuel storage areas and generator rooms, where rapid identification of open flames may be important [12].

Alongside conventional detectors, multi-sensor detection systems are becoming increasingly important. These systems combine different sensing mechanisms, such as smoke, heat, and carbon-monoxide detection, within a single unit. The combination of information from multiple sensors allows the system to assess fire conditions more comprehensively than a single-sensor device. This approach can help distinguish genuine fire conditions from non-fire events and consequently improve overall detection reliability.

The increasing use of multi-sensor systems also reflects a broader movement toward intelligent and integrated fire detection in high-rise buildings. By combining information from different sources, these systems have the potential to reduce both false alarms and missed detections. Their effectiveness, however, depends on appropriate installation, sensor reliability, and integration with the wider building fire-safety infrastructure. Thus, flame detectors and multi-sensor technologies can serve as important complementary components within a comprehensive high-rise fire detection strategy.

Table 2: Comparison of Fire Detection Technologies in High-Rise Buildings [13]

Detection Technology	Primary Detection Mechanism	Major Advantage	Key Limitation	Suitable Application
Ionization Smoke Detector	Detects smoke particles from combustion	Rapid response to fast-flaming fires	May be more prone to nuisance alarms	General occupied areas
Photoelectric Smoke Detector	Detects visible smoke particles	Effective for slow-smoldering fires	Performance may be affected by environmental conditions	Corridors, rooms and circulation areas

Heat Detector	Detects temperature or rapid temperature rise	Resistant to nuisance alarms	Relatively slower response	Kitchens, mechanical rooms and car parks
Flame Detector	Detects infrared or ultraviolet radiation from flames	Rapid identification of open flames	Limited to specific high-risk applications	Generator and fuel-storage areas
Multi-Sensor Detector	Combines smoke, heat and carbon-monoxide sensing	Improves detection reliability and reduces false alarms	More complex and potentially costlier	High-risk and sensitive building areas

2.4 Artificial-Intelligence-Enabled and Smart Detection Systems

A significant development in recent years has been the emergence of AI-enabled detection systems that apply machine-learning algorithms to sensor data streams, closed-circuit video feeds, and building-management-system data to identify fire signatures earlier and more reliably than threshold-based conventional detectors [14]. These systems can, in principle, distinguish between genuine fire conditions and common nuisance sources such as cooking smoke or dust, thereby reducing false-alarm rates that otherwise erode occupant and staff confidence in the alarm system. However, the practical performance of such systems in high-rise buildings depends on sensor placement, network reliability, and the quality of the underlying training data, and empirical evidence on long-term reliability in live deployments remains comparatively limited. Fire dynamics studies further indicate that even a well-designed detection network can underperform if detector spacing and building ventilation pathways are not evaluated jointly with expected fire growth rates on each floor.

2.5 Detection System Layout, Coverage and Integration

The physical layout of a detection network is as important to overall performance as the technology of the individual sensors themselves. Detector spacing standards typically assume a uniform ceiling height and unobstructed airflow, but real high-rise floor plates often include partitioned offices, suspended ceilings, and irregular HVAC return paths that alter how quickly smoke reaches a given sensor. Fire dynamics simulations have shown that detectors positioned according to generic code-based spacing rules can still register meaningfully different response times depending on where within a floor plate a fire originates, particularly on floors served by mechanical ventilation that dilutes or redirects smoke before it reaches the nearest detector. This finding reinforces the case for evaluating detector layout against building-specific airflow and geometry rather than applying uniform spacing assumptions across all floors of a tall building.

Integration between the fire detection network and the broader building management system (BMS) is another factor that increasingly determines real-world performance. When detection signals are tied into BMS functions such as automatic HVAC shutdown, elevator recall, and pressurization of stairwells, the overall response of the building to an incipient fire is considerably faster and more coordinated than when these functions must be triggered manually. Bibliometric evidence indicates that research addressing integrated, systems-level fire safety architecture, rather than isolated detection or suppression components, has expanded steadily over the review period, reflecting an industry-wide recognition that component-level performance alone is an incomplete measure of building fire safety.

3. FIRE SUPPRESSION SYSTEMS IN HIGH-RISE BUILDINGS

Once a fire has been detected, suppression systems are relied upon to control or extinguish it before it can spread vertically or horizontally beyond its point of origin. High-rise buildings typically incorporate a combination of automatic and manual suppression measures [15].

3.1 Automatic Sprinkler Systems

Wet-pipe sprinkler systems are the most common automatic suppression measure in high-rise occupied floors, owing to their reliability and rapid response once a sprinkler head's thermal element activates. Dry-pipe, pre-action and deluge systems are used in specific applications such as unheated spaces, sensitive equipment areas, and high-hazard zones where accidental water discharge must be minimized. The performance of sprinkler systems is strongly dependent on adequate water supply pressure at upper floors, which in tall buildings requires booster pumps and pressure-zoning arrangements that must be regularly tested to remain effective [16].

3.2 Standpipe and Fire Hose Systems

Standpipe systems provide firefighters with a water supply at each floor level, compensating for the practical difficulty of extending hose lines from ground-level fire apparatus to upper floors. The reliability of standpipe systems in commercial high-rise buildings has been found to vary considerably in field evaluations, with issues such as inadequate pressure, valve malfunction, and insufficient hose cabinet maintenance reducing operational readiness at the time of an actual incident [17].

3.3 Gaseous and Clean-Agent Suppression Systems

Data centers, electrical switch rooms, and archive or records storage areas within high-rise buildings often rely on gaseous clean-agent suppression systems, which extinguish fire without leaving the residue or water damage associated with sprinkler discharge. These systems are valued for protecting sensitive equipment but require sealed compartments to be effective, and their applicability is therefore limited to specific occupancies rather than general floor areas.

3.4 Smoke Control and Compartmentation

Beyond direct suppression, smoke control systems, pressurized stairwells, and fire-rated compartmentation play a critical suppression-support role by limiting smoke migration and maintaining tenable conditions along egress routes [18]. Fire dynamics modelling shows that the interaction between an activating suppression system and the building's smoke control strategy strongly influences the time available for safe evacuation, particularly in buildings where the stack effect accelerates vertical smoke movement [19]. Bibliometric evidence indicates that research attention toward integrated smoke-control and active suppression strategies has grown steadily over the past decade, reflecting a broader shift toward treating detection, suppression and smoke management as a single integrated system rather than independent components.

3.5 Fire Extinguishers and Manual Suppression Provisions

Portable fire extinguishers, hose reels, and fire blankets remain a required first-response layer in high-rise buildings, intended for use by occupants or trained fire wardens during the earliest, incipient stage of a fire before automatic systems or the fire service can respond. Field evaluations of commercial high-rise stock have found that while extinguishers are generally present in the numbers required by code, deficiencies such as expired inspection tags, obstructed access, and inadequate staff training on correct use are common, reducing the practical value of this layer of protection even where the physical equipment itself is compliant [20]. This observation reinforces a recurring theme in the literature: the performance gap in high-rise fire protection is as often a function of maintenance, training and human factors as it is of equipment specification [21].

4. PERFORMANCE EVALUATION CRITERIA AND METHODS

Evaluating the performance of fire detection and suppression systems in high-rise buildings requires criteria that capture both technical function and real-world operational readiness [22]. Commonly applied criteria include detection response time, defined as the interval between the onset of a fire signature and system activation; suppression activation reliability, measured as the proportion of installed devices that function correctly when tested or during an actual incident; false-alarm frequency, which affects occupant and staff trust in the system; water supply adequacy, including residual pressure and flow rate at the highest served floor; and the extent to which detection and suppression timing provides sufficient margin for safe evacuation before conditions become untenable [23].

Methodologically, these criteria have been assessed through several complementary approaches in the literature [24]. Field-based evaluation, involving direct inspection, functional testing and review of maintenance records, has been used to assess the operational readiness of installed systems in existing buildings and frequently reveals discrepancies between design specifications and as-built or as-maintained performance [25]. Computational fire dynamics modelling has been used to simulate fire growth, smoke movement and detector or sprinkler response times under varying building geometries and ventilation conditions, allowing evaluation of system layout decisions before construction. Technology-focused performance reviews have assessed the comparative detection accuracy and false-alarm behavior of emerging AI-enabled sensing systems relative to conventional detectors [26]. Finally, bibliometric and systematic literature analysis has been used to identify broader trends in how performance evaluation itself is conducted across the field, highlighting increasing use of data-driven and simulation-based evaluation methods over the past decade [27].

No single evaluation method is sufficient on its own: field evaluation captures real-world degradation and maintenance issues that simulation cannot, while simulation captures dynamic interactions between fire growth and system response that static field inspection cannot observe. A robust performance evaluation framework for high-rise buildings therefore benefits from combining field-based auditing with dynamic modelling and, increasingly, with data generated by smart building management systems [28].

A further methodological consideration is the timescale over which performance is assessed. Single-point-in-time inspections, such as annual compliance audits, capture only the condition of a system now of testing and may not reflect its condition during the intervening period, whereas continuous monitoring through building management or IoT-connected sensors offers a more representative picture of sustained operational readiness [29]. The absence of longitudinal, multi-year performance datasets for high-rise fire safety systems, including emerging AI-enabled equipment, is a recurring limitation noted across the reviewed literature and represents an important direction for future empirical work [30].

6. CONCLUSION

This review has examined the performance of fire detection and suppression systems in high-rise buildings, drawing on field-based evaluation, fire dynamics modelling, technology-focused review and bibliometric analysis. The evidence indicates that conventional detection and suppression technologies remain the operational backbone of high-rise fire safety, but that real-world performance is frequently constrained by maintenance, enforcement and design-assumption gaps rather than by fundamental technological limitations. Building geometry and fire dynamics strongly influence how effectively a given detection and suppression layout performs, underscoring the value of dynamic, building-specific evaluation methods over generic compliance checks alone. Emerging artificial-intelligence-enabled and IoT-connected systems show considerable promise for improving detection speed, reducing false alarms and enabling proactive maintenance, and the broader research trend points firmly toward greater integration of smart technologies into fire safety practice. Realizing these benefits in high-rise buildings will depend on combining technological innovation with rigorous inspection regimes, stronger regulatory enforcement and building-specific performance evaluation, so that the fire safety performance experienced by occupants matches the performance intended at the design stage.

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