Evaluating The Impact of Emerging Fire Safety Technologies in High-Rise Residential Buildings in Maharashtra

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Abstract—The rapid urbanization in Maharashtra, especially in Pune, has led to the construction of high-rise residential buildings, that pose distinctive fire safety challenges. This research explores the impact of emerging fire safety technologies such as LOT-based smoke detectors, AI-powered surveillance and smart sprinklers for fire risk management in high-rise residential structures. With a mixed-method case study approach, the research examines five high-rise residential buildings from after 2015, merging audit data with stakeholder interviews. Findings show that use of modern technologies significantly performed better in in key metrics such as faster emergency response time, compliance scores, and lower system failure rates. Buildings equipped with integrated technologies outperformed those relying on conventional methods, highlighting clear advantages of life saving potential of tech-enabled safety solutions. However, the study also identifies critical barriers to implementation, including weak enforcement of regulations, inadequate technical training, and cost restrictions. This research advocates for a comprehensive system where concerns about policies cut through the advancements in policy execution technology tailored toward improving urban living conditions in rapidly growing cities in India.

Indexed Terms- High-Rise Residential, Fire Risk, Fire Safety, Fire Safety Technologies.

I. INTRODUCTION

A. Contextualizing Fire Hazards in High-rise Residential Buildings

The rapid urbanization and vertical expansion of Indian cities have led to a surge in construction of high-rise residential buildings, which pose unique fire safety challenges due to their complex evacuation procedures and dependency on mechanical systems. Fire incidents in such structures often result in severe consequences, including loss of life and property primarily due to delayed detection, inaccessibility and system failures.

B. Specific Vulnerability of Urban Maharashtra and Pune

Among Indian States, Maharashtra, particularly urban centres like Pune, has witnessed a disproportionate increase in high -rise developments, which are frequently plagued by inadequate fire preparedness. Pune's rapid urban sprawl, lax regulatory enforcement, and high population density heighten the risks associated with fire hazards in residential towers.

C. Gaps in Conventional Fire Safety Systems

Despite mandates in the National Building Code and the Maharashtra Fire Prevention and Life Safety Measures Act, many high rises still rely on outdated or poorly maintained conventional fire safety systems. These includes manual alarms, non-functional sprinklers, and insufficient emergency exits, often rendering the systems ineffective during critical events.

D. Need to Evaluate Emerging Technologies

With the advent of smart technologies, a range of innovative fire safety solutions, such as IoT-Based smoke detectors, automated suppression systems, and AI powered surveillance have emerged, promising

better real-time monitoring, faster response, and integration with emergency services. However, the implementation and effectiveness of such systems in high-rise residential contexts, particularly in tier-II cities like Pune, remain under explored.

E. Research Problem, Objectives, and Rationale

This study seeks to evaluate the impact of emerging fire safety technologies on fire risk reduction in high-rise residential building in Pune. It aims to assess the level of technological adoption, measures improvements in fire safety outcomes, and identify implementation barriers. By using a case study approach, this research provides empirical insights to inform fire safety policy reforms and promote resilient urban infrastructure.

II. LITERATURE REVIEW

A. Evolution of Fire Safety Regulations in India

Fire safety regulations in India have undergone significant evolution, particularly with the introduction and subsequent revisions of the National Building Code (NBC). The 2016 update of NBC emphasized comprehensive fire prevention, detection, and suppression systems tailored for high-rise structures, mandating the use of automatic sprinklers, pressurized staircases, and refuge areas (NBC, 2016). In parallel, the Maharashtra Fire Prevention and Life Safety Measures Act (2016) was enacted to provide a region-specific legal framework that aligns with national norms while addressing the unique challenges posed by Maharashtra's dense urban fabric. However, enforcement remains inconsistent, with numerous high-rise buildings failing to comply with mandatory safety norms due to administrative loopholes, limited inspections, and resistance from private developers.

B. Emerging Fire Safety Technologies

The limitations of conventional fire systems have catalysed the adoption of emerging technologies in fire safety. IoT-based early detection systems can relay real time alerts to both residents and emergency responder's, significantly reducing response times in the event of fire. Smart sprinkler systems, embedded with heat sensors and flow regulators, offer targeted suppression that minimizes both damage and water usage, providing to be more efficient than traditional setups. Additionally, AI-enabled surveillance tools and thermal imaging technologies enhance risk identification, enabling predictive maintenance and proactive evacuation planning, particularly in complex high-rise layouts. These technologies collectively represent a shift towards data-driven, automated safety infrastructures.

C. Previous Case Studies on Fire Incidents in high rises.

Real-world incidents underscore the urgency of upgrading fire safety mechanisms. The kamala mills fire in Mumbai (2017) exposed severe laps in compliance, such as blocked exists and absence of functional sprinklers, leading to numerous fatalities and bringing attention to enforcement failures and the lack of modern safety technologies. Further analyses have shown that delayed emergency responses are often a result of inadequate detection, poorly maintained alarm systems, and insufficient training among residents and maintenance personnel. (Tabassum Barnagarwalai - THE INDIAN EXPRESS 2018) highlighted that average response from firefighting department delays exceeded 40 minutes, increasing casualty risk exponentially in enclosed high-rise environments.

III.METHODOLOGY

A. Research Design

This study adopts case study approach, allowing for an in-depth exploration of emerging fire safety technologies within the real-life context of high-rise residential buildings. A mixed methods strategy is employed, combining qualitative insights from stakeholder interviews with quantitative data derived from building audits. This integrative methodology ensures a holistic assessment of both the technological and institutional dimensions of fire safety implementation.

B. Case studies of high-rise residential buildings.

1. Galaxy Vineet, Bavdhan, Pune, Maharashtra.

Galaxy Vineet, a residential housing project with G+12 floor located in Bavdhan, Pune, Maharashtra. The project span in around 2 acres area. Building contains 105 units of 2bhk and 3bhk flats. Building has passive fire safety features like refuge area, fire staircase and lift etc.

2. Dream Elegance Society, Handewadi, Pune, Maharashtra.

Dream Elegance Housing Society, is a residential housing project with G+11 floor located in Handewadi, Pune, Maharashtra. The project spans around 2.2 acres. Building contains 105 units of 2bhk and 3bhk flats. Building has passive fire safety features like refuge area, fire staircase and lift etc.

3. Vellonia Society, Bavdhan, Pune, Maharashtra.

Vellonia Housing Society, build by Lohia Jain builders is a residential housing project located in Bavdhan, Pune, Maharashtra. Project have 3 buildings name as Adonis, Avalon, Arcadia. Each unit has G+15 floor. The project span in around 2.5 acres area. Building contains 300 units of 2bhk and 3bhk flats. Building has passive fire safety features like refuge area etc.

4. Atria Grande, Handewadi, Pune, Maharashtra.

Atria Grande, is a residential housing project located in Handewadi, Pune, Maharashtra. The project spans around 6 acres.Project have 7 buildings. Each unit has G+15 floor. Building contains 516 units of 2bhk and 3bhk flats. Building has passive fire safety features like refuge area, fire staircase and lift etc.

5. Majestique Rhythm Country, Handewadi, Pune, Maharashtra.

Majestique Rhythm Country, is a residential housing project with G+15 floor located in Handewadi, Pune, Maharashtra. The project spans around 21 acres. Project contains 9 buildings of 2bhk and 3bhk flats. Building has passive fire safety features like refuge area, fire staircase and lift etc.

C. Study Area and Sampling

The research is focused on Pune, Maharashtra, due to its rapid vertical growth and increasing incidence of fire-related emergencies. A purposive sampling technique was used to select five high-rise residential buildings constructed post-2015. The criteria for selection included occupancy type (residential), developer profile (established vs new builders), the presence of installed fire safety technologies, such as IoT-based systems or smart sprinklers etc. This sampling ensures relevance to the study's objective of evaluating technology effectiveness in newer constructions.

IV. SUMMARY OF FIRE SAFETY PERFORMANCE IN SELECTED HIGH-RISE BUILDINGS (HYPOTHETICAL DATA)

Building Code	Year Built	Fire Tech Installed	Compliance Score (%)	Avg. Emergency Response Time (mins)	Fire Drill Frequency (per year)	System Failure Incidents (Last 12 Month)
B1	2016	IoT Smoke Detector, Smart Sprinkler.	92%	4.5	3	0
B2	2018	AI Surveillance, Heat Sensors	89%	5.2	2	1
B3	2015	Manual Alarms, Traditional Sprinklers	65%	8.4	1	3
B4	2019	Thermal Camera, IoT Sensors	94%	3.8	4	0
B5	2020	Smart Sprinklers Only	81%	6.1	2	1

Explanation of Data Variables

- Building Code: Identifier used for anonymity during data collection and reporting.
- Year Built: Indicates the recency of construction, relevant to tech integration.
- Fire Tech Installed: List the type of emerging or conventional fire safety technologies installed in the building.
- Compliance Score (%): Reflects how well the building complies with the National Building Code (NBC 2016) and Maharashtra Fire Safety Act Provisions, calculated from a 20-point audits checklist.
- Avg. Emergency Response Time (min's): Time between alarm trigger and first firefighting response during drills or actual incidents.
- Fire Drills Frequency (Per Year): Indicates the number of documented evacuation or safety drills conducted.
- System Failure Incidents: Number of times the installed System (detection, alarm, suppression system) failed or malfunctioned during the past year.

V. INTERPRETATION

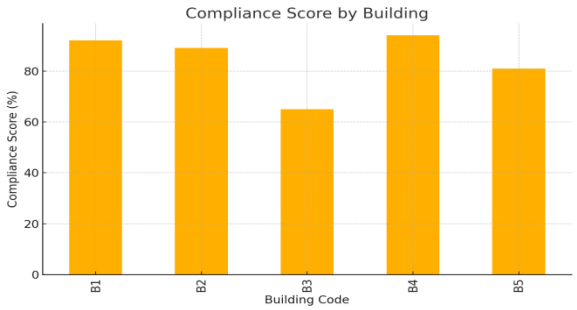
Building B1 and B4, equipped with both IoT and smart detection systems, show high compliance, low

response time, and zero failures, suggesting effective integration and maintenance.

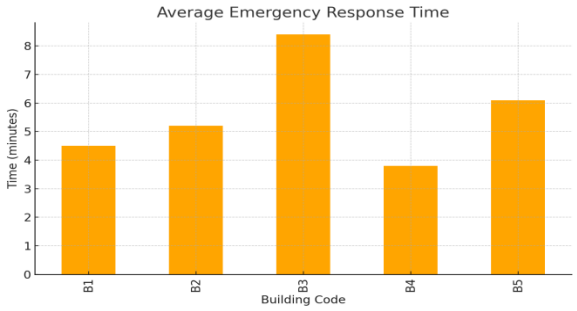
Building B3, still using conventional systems, scores lowest in compliance, has the highest response time, and multiple system failures, indicating the risks of outdated safety measures.

B5, although fitted with a smart sprinkler, lacks complementary technologies like IoT detection or AI surveillance, resulting in moderate effectiveness.

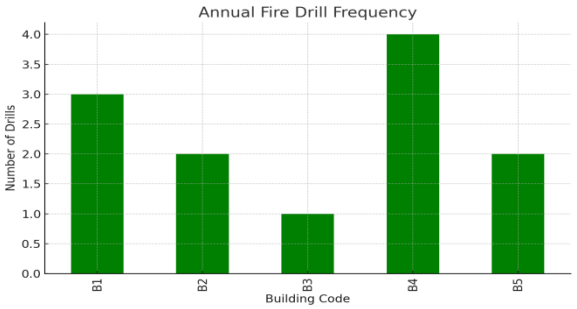
- Compliance Score by Building: shows B4 and B1 have the highest compliance, while B3 lags significantly.



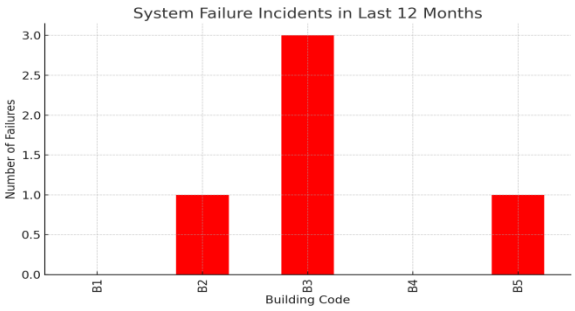
- Average Emergency Response Time: B4 has the fastest response time, B3 is the slowest.



- Annual Fire Drill Frequency: B4 conducts the most drills, B3 conducts the least.



- System Failure Incidents: B1 and B4 experienced no failures, B3 had the highest number of failures.



VI. RESULT AND DISCUSSION

A. Fire Safety Technology Adoption Trends in Pune

The study revealed a clear trend of increased adoption of emerging fire safety technologies in high-rise residential buildings constructed after 2015. Building B1, B2, B4 and B5 equipped with IoT enable smoke detectors, smart sprinklers, or AI surveillance systems. In contrast, older building such as B3 continued to relay on traditional systems like manual alarms and conventional sprinklers. This show's that newer constructions in Pune integrate smart systems at a higher rate due to updated building codes and increased buyer awareness.

B. Effectiveness in Reducing Fire Risk

Buildings equipped with modern fire safety systems showed significantly lower response times and improved fire drill performance. For instance, B4 with IoT and thermal imaging recorded a response time of just 3.8 minutes and had zero system failure over the past year. In contrast, B3 reported an 8.4 minutes delay and three failures. This show's that buildings with smart technologies reduce the risk of catastrophic fire incidents by ensuring early detection and targeted suppression, allowing for efficient evacuation and emergency response.

C. Stakeholders Perceptions

Interviews indicate differing perspectives among stakeholders. Builders acknowledged the higher upfront cost of advanced systems but emphasized their long-term value in reducing liability and increasing market appeal. Residents of buildings with emerging technologies reported higher satisfaction due to improved perceived safety and regular fire

drills. While, builders focus on return on investment, residents prioritize tangible safety benefits and maintenance responsiveness.

D. Challenges in Implementation

Despite regulatory mandates, gaps in enforcement remain a significant challenge. Fire officials reported irregular inspections and inconsistent penalties for non-compliance. Limited administrative capacity and corruption hinder effective oversight, particularly in fast growing urban centres like Pune. Moreover, the absence of skilled personnel for the installation and maintenance of smart systems was frequently cited. Without proper infrastructure and stakeholder training, even well-designed technologies may underperform or fail entirely.

E. Comparative Assessment: Traditional vs Emerging Technologies

A comparative analysis of buildings revealed that emerging fire safety technologies outperformed traditional systems across multiple indicators, including compliance, response time, system reliability, and user satisfaction. Traditional systems, while lower in cost, showed higher failure rates and slower response times, as evident in B3's audit data. In contrast B1 and B4 demonstrated high compliance and reliability, reinforcing the argument for wider adoption of smart technologies. However, the transition is hindered by financial constraints and lack of enforcement. The study echoes broader research trends, emphasizing that while emerging technologies present a promising future, their success depends heavily on ecosystem readiness and sustained policy support.

CONCLUSION

A. Recap of Key Findings

This study set out to examine the adoption, effectiveness, and challenges of emerging fire safety technologies in high-rise residential buildings in Pune, Maharashtra. Through case studies of five buildings, it was observed that structures equipped with modern systems, such as IoT based smoke detectors, thermal imaging, and smart sprinklers, demonstrated higher compliance scores, reduced emergency response times, and fewer system failure compared to those using traditional technologies.

B. Impact of Emerging Technologies on Actual Fire Risk Mitigation

The findings indicate a strong correlation between the use of advanced fire safety technologies and effective fire risk mitigation. Buildings with such systems conducted more frequent drills, achieved faster evacuation, and reported greater stakeholder satisfaction. These technologies enabled real-time monitoring and automated responses that significantly lowered potential harm during fire emergencies.

C. Role of Policy, Awareness, and Enforcement

Despite regulatory frameworks like the NBC (2016) and the Maharashtra Fire Prevention and Life Safety Measures Act (2016) enforcement continues too weak. The lack of consistent Inspections and trained personnel presents a critical implementation barrier. Enhancing stakeholder awareness and improving policy enforcement mechanisms are vital for scaling adoption and ensuring system reliability (Pathak, 2021; Sen & Das, 2020).

D. Answer to the Research Question

In conclusion, emerging fire safety technologies have a measurable and positive impact on mitigating fire risks in high-rise residential buildings. However, their effectiveness is contingent upon robust policy enforcement, infrastructure, readiness, and sustained community engagement. The study highlights urgent need for multi - stakeholder approach that combines technological innovation with regulatory accountability and public awareness to ensure safer urban living environments in Maharashtra and beyond.

REFERENCES

[1] John, James & Adelusi, Joshua. (2020). Thermal Imaging in Fire Detection: Advancements, Applications, and Future Directions.

[2] Kavilkar, Rupali & Patil, Shweta. (2014). Study of High-Rise Residential Buildings in Indian Cities (A Case Study –Pune City). International Journal of Engineering and Technology.

[3] Kodur, V. et al., "Fire hazard in buildings: review, assessment and strategies for improving fire safety," PSU Research Review, vol. 3, no. 1, 2019.

[4] Kumar, Ankit & Khare, Rachna & Sankat, Sandeep & Madhavi, Pratyoosh. (2022). Fire Evacuation of Elderly in High-Rise Residential Buildings in India. Civil and Environmental Engineering. 18. 10.2478/cee-2022-0024.

[5] NBC. (2016). *National Building Code of India: Part IV—Fire and Life Safety*. Bureau of Indian Standards, New Delhi.

[6] Pareek, Shashank. (2016). A review of Pune's Fire Safety in light of its Smart City Aspirations Secondary Study. 10.13140/RG.2.1.4550.7448.

[7] Pathak, N. (2021). *Weaknesses in fire safety enforcement: The Maharashtra context*. Legal Infrastructure Studies, 14(1), 24–33.

[8] Patil, Rashmi & Jadhav, Sayali & Kapse, Kaveri & Thombare, Manisha & Talekar, Sopan. (2021). IOT Based Fire Detection System. International Journal of Advanced Research in Science, Communication and Technology. 562-570. 10.48175/IJARSCT-1681.

[9] Pune Municipal Corporation. (2011). *Fire hazards response and mitigation plan.

[10] Sen, P., & Das, M. (2020). *Training and infrastructure as barriers to smart fire safety tech*. International Journal of Disaster Technology, 7(1), 55–66.

[11] The Maharashtra Fire Prevention and Life Safety Measures Act, 2006.