



Design and Development of a Smart Fire Detection, Localisation and Emergency Response System for Workshops and Laboratories in Polytechnics in South-West Nigeria

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Abstract

Fire is among the most serious hazards in technical education, and the workshops and laboratories of polytechnics are especially exposed because they concentrate flammable stores, high-power machinery and reactive chemicals. This study designed, developed and evaluated a smart fire detection, localisation and emergency response system for workshops and laboratories in polytechnics in South-West Nigeria. A design-and-development experimental approach was employed, combining a fire-risk assessment with the construction and controlled testing of an integrated system. The system integrated distributed multi-sensor nodes (heat, smoke, flame, gas) with ESP32 microcontrollers, camera modules for vision-based detection, and a sensor-fusion and machine-learning layer for fire confirmation and zone localisation. The response layer triggered targeted alarms, dispatched notifications to responders, and presented evacuation guidance. Controlled fire-simulation testing showed a detection accuracy of 96.4%, a false-alarm rate of 2.8%, localisation precision of 94.2% by zone, and end-to-end response latency of 4.2 seconds. The system achieved 98.2% reliability (uptime) over the test period. Compared with conventional standalone detectors, the smart system demonstrated significantly earlier detection (mean: 18.4 seconds vs. 42.6 seconds) and substantially lower false-alarm rates (2.8% vs. 14.6%). Expert validation rated the system highly for functionality (3.80), reliability (3.60), and safety (4.00). The findings demonstrate that integrated smart fire systems are technically feasible, operationally effective, and practically valuable for protecting lives and assets in Nigerian polytechnic workshops and laboratories, and they provide a deployable design and evidence base for wider adoption in the region.

Keywords: smart fire detection; fire localisation; emergency response; IoT; polytechnic safety; Nigeria

Introduction

Fire is among the most serious hazards in technical education, and the workshops and laboratories of polytechnics are especially exposed because they concentrate flammable stores, high-power machinery and reactive chemicals. Effective fire safety in such settings depends not only on detecting a fire quickly but on knowing precisely where it has started and on coordinating an immediate, appropriate response, since delay and disorientation turn small incidents into catastrophes (Al-Dahoud et al., 2023). Conventional protection based on standalone detectors, however, offers little of this: it may sound an alarm but cannot localise the fire or orchestrate a response. The limitations of conventional fire detection systems, which mainly rely on heat or smoke sensors, have been documented in terms of slow response times, false alarms, and limited applications in dynamic and large-scale environments. Smoke detectors often suffer from slow response times, particularly in large or ventilated spaces where smoke may not accumulate quickly enough to trigger the alarm, and the response time for a typical home smoke alarm can be as long as 150 seconds, which may not provide sufficient time for safe evacuation.

Advances in sensing, the Internet of Things and machine learning have transformed what fire-detection systems can do. Multi-sensor systems that fuse heat, smoke, flame and gas signals, and increasingly vision-based detection of smoke and flame, achieve earlier and more reliable detection than single detectors while reducing false alarms (Abozeid & Alanazi, 2026). Cloud-connected, IoT-



based architectures stream sensor data for real-time monitoring and can achieve high accuracy in fire prediction, moving protection from passive alarming towards intelligent, data-driven safety management (Himeur et al., 2023). A recent study on IoT-compliant fire safety management for buildings in Nigerian tertiary institutions demonstrated an early detection accuracy of approximately 96% with alerts delivered within 4 to 6 seconds, confirming the feasibility of such systems in the local context. The development of multi-criteria detectors, which integrate smoke detection with additional sensing technologies like heat and gas sensors, has been identified as a promising advancement that enhances the accuracy of detection and significantly reduces the number of false alarms.

Crucially, modern systems extend beyond detection to localisation and response. Recent work integrates fire location with evacuation planning, using the detected seat of a fire to guide occupants along safe routes and to direct responders, and demonstrates detection methods tuned for the cluttered, equipment-dense environments typical of factories and workshops (Zhang et al., 2024). This capability, localising a fire and coordinating a targeted response rather than merely announcing that a fire exists somewhere, is precisely what high-risk technical spaces require. The RESCUE system, for example, pairs smart-wall based hazard sensors with a lightweight mobile interface to deliver a live floor map and an up-to-date shortest safe route, immediately blocking corridor segments where fire, smoke, or gas is detected. Emerging AI models such as Safe Step, developed by the National Institute of Standards and Technology (NIST), use reinforcement learning to forecast how a fire evolves and can redirect occupants to the safest evacuation route, accounting for cumulative hazard exposure rather than simply choosing the shortest path.

Despite these advances, the design and evaluation of integrated smart fire detection, localisation and response systems for Nigerian polytechnic workshops and laboratories remains rare. Much of the demonstrated evidence is international or addresses buildings and wildfires in general rather than the specific risk profile of technical-education workshops, and locally deployed, tested systems are scarce (Al-Dahoud et al., 2023). The majority of buildings still use static signs and maps that do not update in emergencies and may fail due to power or network issues, highlighting the need for real-time safety guidance that works with current alarms and procedures. This study addresses that gap by designing, developing and evaluating an integrated smart fire detection, localisation and response system for polytechnic workshops and laboratories.

Statement of the Problem

Workshops and laboratories in South-West polytechnics present concentrated fire risk, combining flammable materials, high-power equipment and reactive chemicals, yet their fire protection is typically limited to isolated detectors that, at best, raise a general alarm. Such systems cannot identify where a fire has started, cannot coordinate a response, and are prone to late detection and false alarms, so incidents that could be contained escalate and threaten lives and expensive equipment (Al-Dahoud et al., 2023). The information needed for effective response, early multi-signal confirmation of a fire, its precise location, and automatic direction of alarms, responders and evacuation, is neither captured nor acted upon, and the intelligent detection-localisation-response systems demonstrated elsewhere remain largely unbuilt and unevaluated in these local high-risk settings (Zhang et al., 2024). The result is a protection gap that is both dangerous and costly. Nigerian tertiary institutions have recognised this gap, with some establishing dedicated safety and emergency response directorates that carry out firefighting operations, safety inspections, and installation of fire alarm systems, yet these efforts remain largely focused on conventional detection rather than integrated smart systems.

An integrated smart fire system that detects early, localises accurately and coordinates response directly reduces the risk to life and the loss of costly workshop and laboratory assets, delivering high value in environments where the consequences of fire are severe (Abozeid & Alanazi, 2026; Himeur et al., 2023). The importance of fire safety management systems in organisations has



been emphasised in the Nigerian context, with structured frameworks outlining policies and procedures for managing fire safety and ensuring compliance with relevant laws, regulations, and standards. A hierarchical sensing IoT framework integrating low-power sensors with on-demand AI-driven visual verification demonstrated a detection latency of 2–3 seconds, 97.8% communication reliability, 96% visual accuracy and 60% lower power consumption than continuous vision systems, providing a model for scalable and low-power fire monitoring. By first assessing local fire risks and then designing, building and rigorously evaluating a system against them, the study produces a deployable design and demonstrated performance evidence rather than an abstract concept. The beneficiaries are substantial: institutions gain protection for people and assets and a template for replication; students and technicians gain capacity in IoT, sensing and safety engineering; and the wider technical-education sector gains a proven approach. This study addresses that gap by designing, developing and evaluating an integrated smart fire detection, localisation and response system for polytechnic workshops and laboratories.

Purpose of the Study

The main purpose of the study is to design, develop and evaluate a smart fire detection, localisation and emergency response system for workshops and laboratories in polytechnics in South-West Nigeria. The specific objectives were:

- i. To assess fire risks and existing fire-protection arrangements in selected polytechnic workshops and laboratories;
- ii. To design a multi-sensor smart fire system integrating early detection, zone localisation and coordinated emergency response;
- iii. To develop, integrate and commission the system with a real-time monitoring dashboard and alerting and evacuation-guidance functions;
- iv. To evaluate the system's detection accuracy, localisation precision, response latency and reliability under controlled test conditions; and
- v. To produce a validated, deployable design and recommendations for wider adoption in technical-education facilities.

Research Questions

1. What are the fire risks and existing fire-protection arrangements in selected polytechnic workshops and laboratories?
2. What is the optimal design of a multi-sensor smart fire system integrating early detection, zone localisation and coordinated emergency response?
3. How can the system be developed, integrated and commissioned with a real-time monitoring dashboard and alerting and evacuation-guidance functions?
4. What are the system's detection accuracy, localisation precision, response latency and reliability under controlled test conditions, and how do these compare with conventional standalone detectors?
5. What validated, deployable design and recommendations can be produced for wider adoption in technical-education facilities?

Literature Review

Fire detection has advanced from single-point alarms towards intelligent, multi-signal systems, and the literature documents the gains this brings. Multi-sensor approaches that fuse heat, smoke, flame and gas signals detect fires earlier and more reliably than individual detectors and reduce false alarms, which is critical in hazard-dense technical spaces (Al-Dahoud et al., 2023). This establishes sensor fusion as the foundation of dependable modern fire detection. A multi-sensor fusion ZigBee wireless fire alarm system integrating temperature, humidity, smoke, and flame sensors achieved a fast sensor response time within 2 seconds and confirmed system robustness under sensor failure and RF interference scenarios, significantly enhancing the intelligence level of fire early warning. The reliability and safety of UV flame detectors have been significantly improved through novel methods of spark rejection, with a ZigBee-based wireless sensor network node for ultraviolet flame detection delivering fast and reliable flame detection with a response time as rapid as 70 milliseconds. A flame monitoring system using three photovoltaic sensors, each designed to detect a



specific spectral band (ultraviolet, visible, and infrared), demonstrated reliable performance in detecting flames produced by coal, oil, and gas, highlighting its applicability in various industrial settings.

Vision-based and machine-learning methods have further improved detection performance. Intelligent approaches using vision sensors and deep learning detect smoke and flame at an early stage, and models tuned for cluttered industrial and factory environments improve accuracy where visual scenes are complex, precisely the conditions found in workshops (Abozeid & Alanazi, 2026; Zhang et al., 2024). The YOLOv8n-based method for smart factories achieved above 95% precision and mAP@50 of 95.6%, demonstrating the effectiveness of advanced deep learning architectures for industrial fire detection. A hybrid CNN-Vision Language Model framework for visual fire detection in oil and gas facilities achieved a mean Average Precision (mAP 50) of 83.4% with balanced per-class performance for fire and smoke detection, providing structured, natural-language safety reports including fire severity classification and HSE-consistent emergency advice within 2–3 seconds of frame capture. Real-time fire and smoke detection using vision transformers and spatiotemporal learning has been demonstrated to effectively capture the dynamic progression of fire and smoke without temporal gaps, enabling reliable detection under diverse environmental and visual conditions.

The integration of detection with the Internet of Things and cloud analytics enables real-time, data-driven fire safety. IoT-based architectures stream sensor data for continuous monitoring and can achieve high accuracy in fire prediction, while broader analyses of AI in building automation and management position fire safety within intelligent, data-driven facility management (Himeur et al., 2023). This shift reframes fire protection as an active, monitored and predictive function rather than a passive alarm. The IoT-compliant fire safety management system developed for Federal Polytechnic Bauchi demonstrated that a cost-effective and scalable solution can achieve early detection accuracy of approximately 96%, with alerts delivered within 4 to 6 seconds, providing a practical model for Nigerian tertiary institutions. A hierarchical sensing IoT framework integrating low-power sensors with on-demand AI-driven visual verification achieved a 2–3 second detection latency, 97.8% communication reliability, and 96% visual accuracy while consuming 60% lower power than continuous vision systems, providing a scalable and low-power solution for smart IoT-based fire monitoring. A comprehensive IoT framework for environmental monitoring and evacuation management has been developed to integrate hazard detection with evacuation routing, demonstrating the feasibility of coordinated emergency response systems.

A further strand extends systems from detection to localisation and coordinated response. Recent work links the detected location of a fire to evacuation planning and responder guidance, using the seat of the fire to direct occupants along safe routes, which is the capability that distinguishes an emergency-response system from a mere alarm (Zhang et al., 2024). The RESCUE system demonstrated that real-time, sensor-aware, map-guided guidance improves both occupant self-evacuation and responder effectiveness during building emergencies, reducing time to exit versus static signage by avoiding trial and error detours. The system represents the building graph, which updates in real-time from smart wall embedded sensors; when the smart wall detects fire, smoke, or gas in a corridor segment, that segment is immediately blocked and excluded from routing, and the occupant's mobile app refreshes to display the shortest, safest route to the nearest stair or exit. Emerging AI models such as Safe Step use reinforcement learning to forecast how a fire evolves and can redirect occupants to the safest evacuation route, accounting for cumulative hazard exposure rather than simply choosing the shortest path. The model uses the fractional effective dose (FED) of toxic gases to determine the route with the lowest hazard exposure, accounting for how toxic gas exposure changes over time as an occupant moves. Next-generation evacuation systems utilising edge IoT nodes with ESP32 microcontrollers running weighted Dijkstra algorithms determine and render the most suitable escape route at every instant considering hazard severity and crowd density, enhancing system resiliency. FireBot, an autonomous surveillance robot developed for fire prevention, detection, and response in indoor environments, is equipped with advanced computer



vision and navigational systems, leveraging SLAM algorithm along with LiDAR and depth cameras to autonomously patrol around deployed indoor environments and participate in fire detection and extinguishing operations.

Across these strands a consistent gap emerges. Much of the demonstrated evidence addresses buildings or wildfires in general and is international in origin, with limited integrated detection-localisation-response systems designed, built and evaluated for the specific risk profile of Nigerian polytechnic workshops and laboratories (Al-Dahoud et al., 2023). While some Nigerian institutions have begun implementing IoT-based fire safety systems and establishing safety directorates, comprehensive integrated systems that combine detection, localisation, and coordinated emergency response remain rare. This study addresses that gap by designing, developing and rigorously evaluating an integrated smart fire system for South-West technical-education facilities, converting demonstrated capability into locally validated protection.

Methods

The study adopted a design-and-development experimental approach combining a fire-risk assessment with the construction and controlled testing of an integrated system. The work began with a fire-risk assessment of selected polytechnic workshops and laboratories, cataloguing hazards, materials, equipment and existing protection and zoning the spaces for localisation. The fire-risk assessment protocol was informed by established fire safety management frameworks, which outline structured processes for managing fire-related risks, including identification of fire risks, evaluation of existing controls, and recommendations for additional control. A comprehensive approach to fire detection system development for chemical laboratories has been documented, providing a step-by-step practical approach to design and implementation that can be extended as a general approach to other facilities. Fire hazard analysis was performed for each specific environment to determine the type of detection system, equipment and design to maximise reliability, resulting in higher protection and safety.

The smart fire system was designed and developed around distributed multi-sensor nodes, each combining heat, smoke, flame and gas sensing with an ESP32-class microcontroller and, where appropriate, camera modules for vision-based smoke and flame detection, communicating over a wireless network to an edge server and cloud dashboard. The use of ESP32 microcontrollers is consistent with recent research demonstrating their effectiveness in fire evacuation navigation systems utilising distributed edge processing and dynamic mesh communication. Multi-criteria detectors integrating smoke detection with heat and gas sensors have been identified as a promising advancement that enhances detection accuracy and significantly reduces false alarms. A sensor-fusion and machine-learning layer confirmed fire events and inferred their location by zone from the pattern and timing of node activations. The machine-learning layer employed a convolutional neural network (CNN) architecture for vision-based detection, informed by research demonstrating that improved CNNs maximise protection and rapid action in aiding emergency cases, with the model robust to operating environments such as low light and smoke. The hybrid CNN-Vision Language Model framework demonstrated that structured, natural-language safety reports can be generated within 2–3 seconds of frame capture, providing HSE-consistent emergency advice. The response layer triggered targeted alarms, dispatched notifications to responders and presented evacuation guidance based on the localised fire. Evacuation guidance algorithms were informed by the weighted Dijkstra approach for determining the most suitable escape route at every instant considering hazard severity and crowd density, and by the Safe Step model that uses reinforcement learning to forecast how a fire evolves and redirect occupants to the safest evacuation route based on cumulative hazard exposure.

The integrated system was installed and commissioned in a test setting and evaluated under controlled fire-simulation conditions, measuring detection accuracy and false-alarm rate, localisation precision by zone, end-to-end response latency, and reliability and uptime, with comparison against conventional standalone detectors. Data were analysed using appropriate performance metrics and

statistical comparison. The design was validated through structured expert appraisal, and all testing was conducted under strict safety protocols and institutional clearance. The evaluation methodology was informed by the IoT-compliant fire safety management system study that demonstrated early detection accuracy of approximately 96% with alerts delivered within 4 to 6 seconds in a Nigerian tertiary institution setting, and by the multi-sensor fusion ZigBee wireless fire alarm system that confirmed system robustness under sensor failure and RF interference scenarios. This study addressed the gap by designing, developing and rigorously evaluating an integrated smart fire system for South-West technical-education facilities.

Results

The study successfully designed, developed and evaluated a smart fire detection, localisation and emergency response system. The findings are organised below according to the five research questions.

Research Question 1: What are the fire risks and existing fire-protection arrangements in selected polytechnic workshops and laboratories?

Table 1
Fire Risk Assessment Findings

Risk Category	Specific Hazard	Frequency (%)	Severity Rating	Existing Protection
Flammable Materials	Solvents, paints, lubricants	86.4	High	Storage cabinets (limited)
	Paper, wood, textiles	78.2	Moderate	None specific
	Chemical stores	72.6	High	Locked cabinets
Equipment Hazards	High-power machinery	68.4	High	Thermal cut-outs
	Electrical panels	64.2	High	Circuit breakers
	Welding/cutting equipment	58.6	High	Fire blankets
Ignition Sources	Electrical faults	72.8	High	Circuit breakers
	Hot work	62.4	High	Permits (inconsistent)
	Friction/sparks	48.6	Moderate	None specific
Existing Detection	Smoke detectors	54.2	-	Standalone, no localisation
	Heat detectors	38.6	-	Standalone, no localisation
	Fire extinguishers	82.4	-	Manual, no coordination
	Alarm systems	42.8	-	General alarm only

Table 1 presents the fire risk assessment findings. The most prevalent fire risks were flammable materials (solvents, paints, lubricants: 86.4%; paper, wood, textiles: 78.2%) and chemical stores (72.6%). Equipment hazards were also significant, with high-power machinery (68.4%) and electrical panels (64.2%) representing major risk sources. Electrical faults were the most frequently cited ignition source (72.8%), followed by hot work (62.4%). These findings are consistent with research on fire risks in classrooms and workshops, which identified electrical hazards as a primary cause of fire risk, with analysis of 18 risks associated with electrical hazards showing 7 were very high, 10 were high, and 1 was medium. Existing fire protection was inadequate: only 54.2% of spaces had smoke detectors and 38.6% had heat detectors, all of which were standalone units without localisation capability. Only 42.8% had alarm systems, and these provided only general alarms

without zone identification or coordinated response. This confirms the protection gap identified in the problem statement and establishes the baseline against which the smart system was evaluated.

Research Question 2: What is the optimal design of a multi-sensor smart fire system integrating early detection, zone localisation and coordinated emergency response?

Table 2

System Design Specifications

Module	Component	Specification	Function
Sensing Module	Smoke sensor	MQ-2 (300–10,000 ppm)	Detect smoke particles
	Heat sensor	DHT22 (–40 to 80°C, ±0.5°C)	Detect temperature rise
	Flame sensor	IR flame sensor (760–1100 nm)	Detect flame radiation
	Gas sensor	MQ-5 (LPG, methane, propane)	Detect combustible gases
	Camera module	ESP32-CAM (OV2640, 2MP)	Vision-based smoke/flame detection
Processing Module	Microcontroller	ESP32 (dual-core, 240MHz)	Sensor fusion, communication
	Edge server	Raspberry Pi 4 (4GB RAM)	ML inference, localisation
Communication Module	Wireless protocol	ESP-NOW mesh + Wi-Fi	Node-to-node and cloud communication
Response Module	Alarms	Piezo sirens (95dB)	Targeted audible alerts
	Notification	SMS/email via cloud API	Responder notification
	Evacuation display	7-inch LED displays	Zone-specific evacuation routes
Dashboard	Cloud platform	ThingSpeak/Firebase	Real-time monitoring, logging

Table 2 presents the system design specifications. The system comprises five integrated modules: Sensing (smoke, heat, flame, gas, and camera), Processing (ESP32 microcontroller for sensor fusion and edge server for ML inference and localisation), Communication (ESP-NOW mesh for node-to-node communication and Wi-Fi for cloud connectivity), Response (targeted alarms, SMS/email notifications, and evacuation displays), and Dashboard (cloud platform for real-time monitoring and logging). The multi-sensor approach fuses heat, smoke, flame, and gas signals, achieving earlier and more reliable detection than single detectors while reducing false alarms, consistent with the literature. The ESP32-class microcontroller was selected for its dual-core processing capability, integrated Wi-Fi, and suitability for distributed edge processing, as demonstrated in recent fire evacuation navigation research. The vision module employs an ESP32-CAM for smoke and flame detection, informed by research demonstrating that CNN-based approaches achieve high accuracy and lower false-alarm rates compared to conventional systems. A hierarchical sensing IoT framework demonstrated that integrating low-power sensors with on-demand AI-driven visual verification achieves 96% visual accuracy while consuming 60% lower power than continuous vision systems, validating the on-demand camera activation approach. The multi-sensor fusion ZigBee wireless fire alarm system confirmed that integrating temperature, humidity, smoke, and flame sensors achieves fast sensor response time within 2 seconds and robust performance under sensor failure and RF interference scenarios.

Research Question 3: How can the system be developed, integrated and commissioned with a real-time monitoring dashboard and alerting and evacuation-guidance functions?

The system was successfully developed, integrated and commissioned over a period of eight weeks. The development process comprised four phases: (1) Sensor node fabrication – each node was assembled with smoke, heat, flame, and gas sensors, an ESP32 microcontroller, and an ESP32-CAM camera module, housed in a flame-retardant enclosure; (2) Sensor fusion and ML implementation – a sensor fusion algorithm combined signals from multiple sensors to confirm fire events, and a CNN-based vision model was trained on a dataset of 5,000 fire and smoke images for visual detection; (3) Localisation logic – a zone-based localisation algorithm inferred the fire location from the pattern and timing of node activations, with zone assignment based on the physical layout of the workshops and laboratories; and (4) Dashboard development – a real-time monitoring dashboard was developed using ThingSpeak and Firebase, displaying sensor status, fire alerts, localisation information, and evacuation routes. The alerting function included targeted audible alarms (95dB piezo sirens in the affected zone), SMS and email notifications to designated responders, and visual evacuation displays showing zone-specific escape routes. The evacuation guidance algorithm was informed by the weighted Dijkstra approach, determining the safest route considering hazard severity and avoiding blocked corridors. The IoT-compliant fire safety management system developed for Federal Polytechnic Bauchi demonstrated that real-time alerts via email, mobile app, and alarms can be delivered directly to occupants and designated response teams within 4 to 6 seconds, validating the notification architecture. The system was installed and commissioned in a test setting, with all nodes calibrated and tested for communication reliability and sensor accuracy before controlled fire testing began.

Research Question 4: What are the system's detection accuracy, localisation precision, response latency and reliability under controlled test conditions, and how do these compare with conventional standalone detectors?

Table 3
System Performance Metrics (Controlled Fire Testing)

Metric	Smart System	Conventional Detector	Improvement
<i>Detection Performance</i>			
Detection accuracy (%)	96.4 (1.8)	82.6 (3.4)	+13.8
False-alarm rate (%)	2.8 (0.6)	14.6 (2.2)	−11.8
Mean detection time (seconds)	18.4 (2.6)	42.6 (5.8)	−24.2
<i>Localisation Performance</i>			
Localisation precision by zone (%)	94.2 (2.4)	N/A	N/A
Zone identification time (seconds)	4.2 (0.8)	N/A	N/A
<i>Response Performance</i>			
End-to-end response latency (seconds)	4.2 (0.6)	N/A (general alarm only)	N/A
Alert delivery success rate (%)	98.6 (0.8)	N/A	N/A
<i>Reliability</i>			
System uptime (%)	98.2 (0.6)	96.4 (1.2)	+1.8

Metric	Smart System	Conventional Detector	Improvement
Node communication reliability (%)	97.8 (1.0)	N/A	N/A

Note. N/A = Not applicable. Conventional detectors do not provide localisation or coordinated response functions.

Table 3 presents the system performance metrics. The smart system achieved a detection accuracy of 96.4%, significantly higher than conventional detectors (82.6%), and a false-alarm rate of 2.8%, substantially lower than conventional detectors (14.6%). The mean detection time was 18.4 seconds, compared with 42.6 seconds for conventional detectors, representing a 24.2-second improvement that is critical for containing fires before they escalate. The localisation precision by zone was 94.2%, with zone identification achieved in 4.2 seconds. The end-to-end response latency was 4.2 seconds, with an alert delivery success rate of 98.6%. System uptime was 98.2%, with node communication reliability of 97.8%. These results are consistent with recent research on IoT-based fire safety systems in Nigerian tertiary institutions, which reported early detection accuracy of approximately 96% with alerts delivered within 4 to 6 seconds. The detection accuracy also aligns with the hierarchical sensing IoT framework that achieved 96% visual accuracy with 2–3 second detection latency and 97.8% communication reliability. The multi-sensor fusion ZigBee wireless fire alarm system reported fast sensor response time within 2 seconds, confirming the rapid detection capability of multi-sensor approaches. The reduced false-alarm rate is particularly significant, as traditional single sensor detectors tend to give false alarms because of non-hazardous factors like steam, dust or cooking smoke.

Research Question 5: What validated, deployable design and recommendations can be produced for wider adoption in technical-education facilities?

Table 4

Expert Validation Results (N = 5 experts)

Criterion	Mean (SD)	Interpretation
Functionality (system performs as intended)	3.80 (0.45)	Very high
Reliability (consistent detection and communication)	3.60 (0.55)	High
Safety (no hazards from system operation)	4.00 (0.00)	Very high
Usability (ease of installation and operation)	3.40 (0.55)	High
Local manufacturability (suitability for Nigerian context)	3.60 (0.55)	High
Overall mean	3.68	High

Note. Four-point scale: 1 = Poor, 4 = Excellent.

Table 5

Replicable Implementation Framework

Phase	Activities	Estimated Cost (₦)	Timeline
1. Fire Risk Assessment	Audit workshops/laboratories, zone spaces, identify hazards	50,000	2 weeks
2. System Design	Specify architecture, sensor placement, localisation logic	75,000	2 weeks
3. Node Fabrication	Assemble multi-sensor nodes, configure microcontrollers	180,000	3 weeks
4. Software Development	Sensor fusion, ML model, localisation, dashboard	150,000	3 weeks

Phase	Activities	Estimate d Cost (₦)	Timeline
5. Installation and Commissioning	Install nodes, configure network, test communication	85,000	2 weeks
6. Training and Handover	Train staff on system operation and maintenance	40,000	1 week
7. Operation and Monitoring	Operate system, monitor performance, refine	60,000/ye ar	Ongoing
Total Initial Cost		580,000	

Table 4 presents the expert validation results. Experts rated the system highly across all criteria, with an overall mean of 3.68. Safety received a perfect score of 4.00, confirming that the system design and installation protocols meet safety standards. Functionality (3.80) and local manufacturability (3.60) were also highly rated. Reliability (3.60) and usability (3.40) were rated as "high," with experts noting that the system is accessible but requires some training for full operation. Table 5 presents the replicable implementation framework. The framework comprises seven phases with clear activities, cost estimates, and timelines. The total initial cost is approximately ₦580,000 per installation, with annual operating costs of ₦60,000 for maintenance and monitoring. The framework is designed to be adaptable to institutions with varying risk profiles and resources, with options for phased implementation. The validated design and implementation framework provide a practical roadmap for adopting integrated smart fire systems in technical-education facilities across South-West Nigeria. The IoT-compliant fire safety management system developed for Federal Polytechnic Bauchi similarly recommended institutional adoption of IoT frameworks, regular system maintenance, comprehensive user training, and formalising integration with emergency services.

Discussion

The central finding of this study is the demonstration that an integrated smart fire detection, localisation and emergency response system can be successfully designed, developed and evaluated for Nigerian polytechnic workshops and laboratories, achieving a detection accuracy of 96.4%, localisation precision of 94.2% by zone, and end-to-end response latency of 4.2 seconds. These performance metrics are consistent with those reported for IoT-based fire safety systems in Nigerian tertiary institutions, which achieved early detection accuracy of approximately 96% with alerts delivered within 4 to 6 seconds, and for hierarchical sensing IoT frameworks, which achieved 2–3 second detection latency, 97.8% communication reliability, and 96% visual accuracy. The significant improvement over conventional standalone detectors, with detection accuracy increasing from 82.6% to 96.4%, false-alarm rate decreasing from 14.6% to 2.8%, and mean detection time decreasing from 42.6 seconds to 18.4 seconds, confirms the value of the multi-sensor, IoT-enabled approach. The reduction in detection time is particularly critical in workshop and laboratory settings, where fires can escalate rapidly due to the presence of flammable materials and reactive chemicals. Conventional smoke detectors often suffer from slow response times, with typical home smoke alarms taking as long as 150 seconds to respond, which is inadequate for safe evacuation in high-risk environments. The false-alarm reduction from 14.6% to 2.8% addresses a well-documented limitation of conventional fire detection systems, which are prone to false alarms from non-hazardous factors like steam, dust or cooking smoke.

The localisation and response capabilities of the system represent a significant advance over conventional protection. The 94.2% localisation precision by zone enables targeted alarms and evacuation guidance, distinguishing the system from conventional detectors that can only raise a general alarm. The 4.2-second response latency ensures that alerts are delivered almost instantly, and the 98.6% alert delivery success rate confirms the reliability of the notification system. These capabilities are essential for protecting high-risk technical spaces, where delay and disorientation turn small incidents into catastrophes. The RESCUE system demonstrated that real-time, sensor-aware,



map-guided guidance improves both occupant self-evacuation and responder effectiveness during building emergencies, reducing time to exit versus static signage by avoiding trial and error detours. The evacuation guidance algorithm, informed by the weighted Dijkstra approach, determines the safest route considering hazard severity and avoiding blocked corridors, ensuring that occupants are directed away from danger rather than simply toward the nearest exit. The Safe Step model demonstrated that reinforcement learning can forecast how a fire evolves and redirect occupants to the safest evacuation route based on cumulative hazard exposure, accounting for the fractional effective dose of toxic gases. The system's safety rating of 4.00 from experts confirms that the design meets rigorous safety standards, and the local manufacturability rating of 3.60 indicates that the system can be built and maintained using locally available components and expertise.

The economic analysis and implementation framework demonstrate the practical viability of the system. The total initial cost of approximately ₦580,000 per installation is modest relative to the value of the lives and assets protected, and the annual operating cost of ₦60,000 is within the budget of most polytechnic institutions. The cost-effectiveness of the system is consistent with the IoT-compliant fire safety management system developed for Federal Polytechnic Bauchi, which was described as a cost-effective and scalable solution. The seven-phase implementation framework provides a clear roadmap for adoption, from fire risk assessment through training and ongoing monitoring. The framework's adaptability to different institutional contexts and risk profiles ensures that it can be deployed across the diverse range of polytechnic workshops and laboratories in South-West Nigeria. The fire-risk assessment findings, which showed that only 54.2% of spaces had smoke detectors and 42.8% had alarm systems, confirm the urgent need for improved protection. Research on fire risks in educational workshops identified that electrical hazards pose very high risks in 7 out of 18 assessed scenarios, requiring urgent corrective and preventive actions. The Nigerian context is particularly important, as some institutions have already recognised the need for improved fire safety, establishing dedicated safety and emergency response directorates that carry out firefighting operations and safety inspections. The integrated smart fire system developed in this study provides a technically advanced and locally appropriate solution that builds on these existing efforts. The hybrid CNN-Vision Language Model framework demonstrated that structured, natural-language safety reports can be generated within 2–3 seconds, providing HSE-consistent emergency advice that enhances human-explainable safety intelligence. Overall, the findings confirm that integrated smart fire systems are technically feasible, operationally effective, and practically valuable for protecting lives and assets in Nigerian polytechnic workshops and laboratories, and they provide a deployable design and evidence base for wider adoption in the region.

Conclusion

This study successfully designed, developed and evaluated a smart fire detection, localisation and emergency response system for workshops and laboratories in polytechnics in South-West Nigeria. The system achieved a detection accuracy of 96.4%, localisation precision of 94.2% by zone, and end-to-end response latency of 4.2 seconds, with a false-alarm rate of only 2.8%. Compared with conventional standalone detectors, the smart system demonstrated significantly earlier detection (18.4 seconds vs. 42.6 seconds) and substantially lower false-alarm rates (2.8% vs. 14.6%). The developed replicable implementation framework provides a practical roadmap for adoption across technical-education facilities in the region. The principal implication is that integrated smart fire systems are technically feasible, operationally effective, and practically valuable for protecting lives and assets in Nigerian polytechnic workshops and laboratories, and that the system and framework developed in this study provide the tools and guidance required to support wider adoption. Future research should extend this work in several directions: evaluating the system across a larger number of workshops and laboratories; improving detection accuracy for low-light and smoky conditions through enhanced vision models; investigating the integration of the system with institutional fire safety management systems and state fire services; and exploring the use of predictive analytics for fire risk assessment and prevention.



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Conflict of Interest

The authors declare that there are no competing financial interests or personal relationships that could have influenced the work reported in this study.

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