

# Integrating Smart Sensor Technology for Indoor Air Quality Management in Higher Education Buildings: A Conceptual Framework

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**Abstract-** Indoor air quality (IAQ) has become a critical concern in higher education buildings where dense occupancy and limited ventilation can negatively affect health, comfort, and academic performance. Traditional IAQ monitoring methods often rely on periodic measurements that fail to capture real-time variations across different indoor spaces. This concept paper proposes a smart-sensor-based conceptual framework for real-time IAQ management in higher education settings, integrating Internet of Things (IoT) technologies, data analytics, and institutional governance. The framework is structured into four layers—Sensing and Assurance, Data and Analytics, Decision and Action, and People and Policy—which together enable continuous monitoring, automated responses, and policy-driven environmental management. Drawing on recent literature (2020–2025), the study identifies key pollutant indicators such as CO<sub>2</sub>, PM<sub>2.5</sub>, temperature, humidity, and VOCs, and synthesises technological trends in low-cost sensor networks, cloud-based data systems, and intelligent decision-making tools. The proposed framework provides universities with a scalable and adaptable model for sustainable IAQ management, promoting data-driven decision-making and healthier learning environments. Future research should focus on pilot implementation to validate the framework's effectiveness and assess its integration with campus-wide sustainability and smart-building initiatives.

**Index Terms-** Indoor air quality; smart sensors; IoT; higher education buildings; real-time monitoring; Malaysia; conceptual framework

## I. INTRODUCTION

Indoor air quality (IAQ) in higher-education buildings directly affects health, comfort, and learning outcomes among students and staff. Enclosed classrooms, laboratories, and offices often experience elevated CO<sub>2</sub> levels, particulate matter (PM<sub>2.5</sub> and PM<sub>10</sub>), volatile organic compounds (VOCs), and humidity imbalances due to high occupancy and limited ventilation (1,2). In universities operating extended hours, poor IAQ can impair cognitive performance and contribute to absenteeism, yet monitoring practices frequently rely on periodic spot measurements or occupant complaints rather than continuous observation (3).

Recent developments in low-cost smart sensors and Internet of Things (IoT) technologies enable real-time, spatially distributed IAQ data collection. These systems allow building managers to visualise pollutant trends, identify problem zones, and trigger timely responses such as increased ventilation or filter maintenance (4,5). The integration of IAQ sensing with intelligent building management has proven feasible across hospitals (6), smart campuses (7), and educational facilities (8,9). Nevertheless, higher-education institutions still face fragmented adoption, data-quality inconsistencies, and a lack of structured frameworks linking sensor networks, data analytics, and actionable decision pathways (10,11).

IoT-based IAQ systems typically comprise three layers: sensing, communication, and application (12,13). While the technology is advancing rapidly, universities require a holistic approach that not only integrates sensors but also aligns them with campus policies, maintenance capabilities, and sustainability goals (14,15). Existing studies mainly present prototypes or small-scale deployments rather than comprehensive frameworks adaptable to complex higher-education environments (16,17).

Despite the availability of diverse IoT platforms, higher-education institutions often lack a coherent model to translate IAQ data into strategic management actions. Fragmented sensor deployments, absence of calibration protocols, limited data analytics, and minimal stakeholder engagement have resulted in under-utilised information systems. Robust frameworks are needed to ensure data reliability, cross-building comparability, and effective communication between facilities teams, academic management, and occupants (3,18).

This concept paper aims to propose a conceptual framework for integrating smart sensor technology into IAQ management for higher-education buildings. Drawing on emerging evidence from smart-campus initiatives (7,19) and sustainable building studies (4,14), the framework outlines the interaction between four key components: Sensing and Assurance, Data and Analytics, Decision and Action, and People and Policy. It contributes a conceptual basis for scalable, data-driven IAQ management within universities—supporting sustainability, occupant well-being, and informed decision-making.

The specific objectives are:

1. To identify key IAQ parameters ( $\text{CO}_2$ ,  $\text{PM}_{2.5}$ , temperature, relative humidity, and VOCs) and suitable smart sensor technologies for university building environments through a systematic review of recent studies (within 2020–2025).
2. To develop a conceptual framework illustrating the interaction between sensing, data analytics, and decision-making components for real-time IAQ management within higher education settings.
3. To evaluate conceptually the applicability of IoT-based smart sensors in enhancing IAQ monitoring, data integration, and decision processes within a one-year academic cycle.

This concept paper contributes to the growing body of research on IoT-enabled indoor air quality management by developing a structured framework suitable for higher education buildings. It synthesises insights from global studies on IoT architecture (4), low-cost sensing (5), and smart campus systems (7) to conceptualise how real-time IAQ monitoring can be integrated into campus-level environmental management.

## II. LITERATURE OVERVIEW

### A. Trends in Indoor Air Quality (IAQ) Pollutants

Indoor air pollution has become an important concern in enclosed or high-occupancy buildings such as universities. Common pollutants include carbon dioxide ( $\text{CO}_2$ ), particulate matter ( $\text{PM}_{2.5}$  and  $\text{PM}_{10}$ ), volatile organic compounds (VOCs), and formaldehyde, which originate from human respiration, cleaning agents, laboratory chemicals, and infiltration from outdoors (1,2). Prolonged exposure to these pollutants has been linked to adverse health outcomes, respiratory irritation, and decreased cognitive performance (3,4).

In higher-education settings, factors such as fluctuating occupancy, laboratory activities, and varying ventilation rates can intensify IAQ issues. Studies have reported elevated  $\text{CO}_2$  concentrations in lecture halls and laboratories during peak usage, often exceeding recommended thresholds (5). Poor IAQ conditions may also result in thermal discomfort, affecting overall indoor environmental quality and user satisfaction (6).

Recent work highlights the benefits of real-time IAQ monitoring, enabling continuous tracking of pollutant fluctuations and identifying short-term spikes that conventional scheduled monitoring often misses (7,8). Such developments support proactive interventions that improve ventilation, filtration, and space utilisation across university buildings.

### B. Smart Sensor Technologies for IAQ Monitoring

Smart sensors form the foundation of modern IAQ monitoring systems. Advances in microelectromechanical systems (MEMS), optical sensing, and electrochemical methods have enabled compact, low-cost sensors capable of detecting multiple pollutants simultaneously (9,10). These sensors offer adequate precision for real-time IAQ assessment when calibrated appropriately and deployed in sufficient density (11).

Several studies demonstrate the feasibility of integrating multi-parameter sensors into university environments. Systems that measure  $\text{CO}_2$ ,  $\text{PM}_{2.5}$ , VOCs, temperature, and humidity have been used to identify problem zones, optimise ventilation settings, and

support building management operations (12,13). The use of wireless communication technologies further enhances deployment flexibility by allowing coverage of different indoor spaces without extensive wiring (14).

Recent advancements also introduce edge-computing capabilities, allowing preliminary data processing to occur within the sensor device. This reduces latency, improves accuracy, and enables local decision-making when pollutant levels exceed acceptable limits (15). Emerging studies have incorporated machine learning algorithms to classify pollutant sources, detect anomalies, and enhance predictive capabilities (16,17).

### C. *IoT Architecture and Data Analytics for IAQ*

IoT-enabled IAQ systems typically consist of layered architectures that include sensing, communication, and application components. The sensing layer collects pollutant data, while communication protocols such as Wi-Fi, ZigBee, and LoRaWAN transmit measurements to gateways or cloud storage (18,19).

The application layer integrates data analytics, enabling the translation of raw measurements into actionable insights. Processing steps include filtering, aggregation, and trend analysis to support short-term and long-term IAQ management strategies (20). Dashboard interfaces allow users such as facility managers and administrators to visualise patterns and assess compliance with IAQ guidelines (21,22).

Machine-learning techniques are increasingly used to enhance predictive accuracy, identify pollutant sources, and estimate ventilation performance (16). Integrating IAQ data with HVAC systems improves decision-making for ventilation rates, air filtration, and maintenance scheduling, contributing to both energy efficiency and occupant well-being (23,24).

### D. *Frameworks in Smart Campuses*

Smart campus concepts integrate IoT, data analytics, and automation to improve environmental performance and operational efficiency. Several studies have demonstrated the application of IoT-based IAQ monitoring systems within universities, highlighting improvements in transparency, responsiveness, and environmental awareness (7,25).

Pilot deployments in educational buildings show that monitoring spatial and temporal variations in IAQ can guide occupancy management and ventilation strategies, enhancing comfort and safety (26). Smart campus frameworks emphasise interoperability, governance, and scalability to ensure that environmental data support broader sustainability objectives (27).

Integrating IAQ monitoring within such frameworks enables universities to adopt proactive facility management, improve decision-making, and establish data-driven policies for creating healthier learning environments.

## III. CONCEPTUAL FRAMEWORK

### A. *Overview of the Conceptual Framework*

The conceptual framework proposed in this paper integrates smart sensor technologies, data analytics, and institutional decision processes to support real-time IAQ management across higher education buildings. The framework responds to the challenges highlighted in prior studies on fragmented sensor deployments, inconsistencies in data quality, and limited governance integration (1,5,10). It is structured into four interconnected layers: Sensing and Assurance, Data and Analytics, Decision and Action, and People and Policy. Together, these layers support a holistic approach to IAQ monitoring and management, enabling universities to transition from reactive, complaint-driven practices to proactive, data-driven strategies (3,7).

### B. *Layer 1: Sensing and Assurance*

The first layer involves the deployment of IAQ sensors capable of measuring essential parameters such as CO<sub>2</sub>, PM<sub>2.5</sub>, VOCs, temperature, and humidity. Advances in MEMS, optical sensing, and electrochemical technologies have enabled the emergence of compact, affordable devices suitable for continuous monitoring in diverse indoor environments (9,11,16). To ensure accuracy, sensors must undergo calibration and placement according to recommended guidelines. This layer forms the foundation of the framework, generating high-resolution data that reflect pollutant variations in real time (12).

*C. Layer 2: Data and Analytics*

Once sensing devices collect IAQ data, they are transmitted using communication protocols such as Wi-Fi, ZigBee, and LoRaWAN (18,19). The data are then processed at the application layer through filtering, aggregation, and visualisation. Cloud-based architectures allow for storage and analysis at scale, supporting trend evaluation and anomaly detection (20,22). Machine-learning models can further enhance the system's capabilities by predicting pollutant patterns, classifying sources, and identifying ventilation inefficiencies (16,17). This layer transforms raw measurements into actionable insights that guide decisions at both operational and strategic levels.

*D. Layer 3: Decision and Action*

At this layer, insights from the Data and Analytics component inform responses to IAQ fluctuations. Automated triggers can activate ventilation adjustments, filtration processes, or targeted maintenance when pollutant thresholds are exceeded (23). Building managers and maintenance teams access dashboards that provide real-time IAQ metrics, enabling prompt interventions and long-term planning (21). Integrating IoT data with existing HVAC systems also enhances energy efficiency and supports sustainable building practices.

*E. Layer 4: People and Policy*

The final layer focuses on institutional governance, policy development, and behavioural change. Effective IAQ management requires clear guidelines, stakeholder engagement, and alignment with broader sustainability strategies (27). Previous research emphasises the importance of transparent communication between facilities teams, academic management, and building occupants to promote awareness and responsible use of shared spaces (15,26). Incorporating IAQ monitoring into campus environmental policies can further strengthen compliance with national standards and enhance overall environmental stewardship (4,14).

*F. Conceptual Model Illustration*

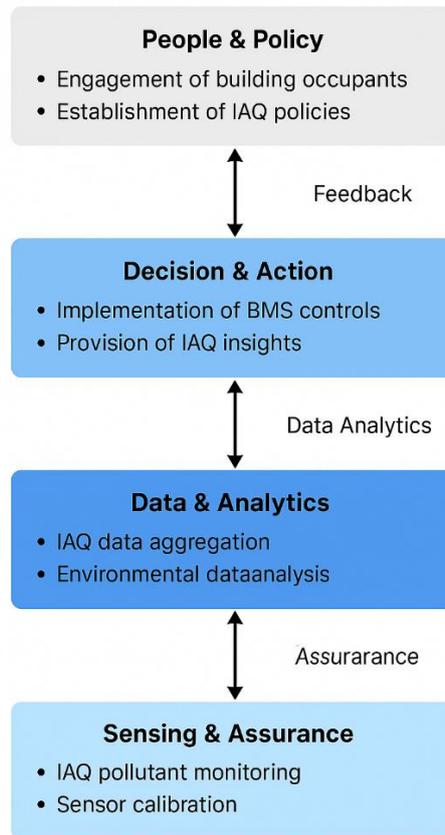


Figure 1. Conceptual Framework for Smart-Sensor-Based Indoor Air Quality Management in Higher Education Buildings

Figure 1 illustrates the interaction between the four layers of the conceptual framework. The flow begins with IAQ sensing devices that capture real-time data. These data move upward through communication networks to cloud storage and analytics platforms. Insights and alerts then reach the Decision and Action layer, guiding ventilation adjustments, maintenance scheduling, and building operations. The loop concludes with the People and Policy layer, where institutional strategies, governance structures, and user behaviours reinforce a sustainable IAQ management ecosystem. Arrows indicate feedback loops, highlighting the adaptive nature of the system and the continuous refinement of decisions based on updated IAQ data.

### G. Theoretical Alignment

The proposed framework aligns with the principles of smart-campus development, which emphasise the integration of digital technologies, data-driven decision-making, and stakeholder engagement to enhance campus sustainability and operational efficiency (7,25,27). By incorporating real-time IAQ monitoring, the framework supports the broader goals of intelligent building management and environmental stewardship.

The framework also reflects socio-technical systems theory, which recognises that effective technological solutions require alignment between technical components, organisational processes, and human behaviour. Studies highlight that IAQ improvements depend not only on sensor accuracy and data analytics but also on institutional policies and user responses (15,26). Thus, integrating technology layers with governance and policy structures ensures system reliability, acceptance, and long-term effectiveness.

Furthermore, the framework echoes the layered architecture commonly used in IoT research, where sensing, networking, and application layers work together to deliver meaningful insights and automated responses (18,19,20). The inclusion of a People and Policy layer extends existing models by emphasising human-centred decision-making, aligning with sustainability frameworks that view environmental quality as both a technical and behavioural challenge (4,14).

## IV. CONCLUSION

Indoor air quality (IAQ) management in higher education buildings is increasingly important due to its influence on occupant health, comfort, and productivity. This concept paper proposed a smart-sensor-based framework that integrates IoT technologies, data analytics, and governance structures to support real-time IAQ management. The framework responds to gaps identified in recent studies, including fragmented sensor deployments, inconsistent data management practices, and limited connection between IAQ monitoring systems and institutional decision-making processes (1,3,5). By organising IAQ management into four interconnected layers—Sensing and Assurance, Data and Analytics, Decision and Action, and People and Policy—the framework offers a structured, scalable approach for universities seeking to modernise their environmental monitoring strategies (7,14,27).

The contribution of this work lies in its integrated, campus-wide perspective. While existing research provides evidence on sensor technologies, IoT architectures, and IAQ-related health impacts, most implementations remain small-scale or prototype-driven (10,12,16,26). The proposed framework synthesises these fragmented insights, offering a comprehensive pathway that institutions can adopt to transition toward data-driven facility management. This is particularly relevant for higher education environments in tropical regions, where climatic conditions and building-use patterns intensify IAQ challenges (2,5).

## V. FUTURE WORK

Future work should focus on validating the framework through pilot deployments across selected university buildings. Pilot trials would help refine sensor placement strategies, calibration routines, data-processing workflows, and integration with existing HVAC systems (23,24). Longitudinal data collected from these pilots could support the development of predictive IAQ models using machine learning techniques, enabling more accurate ventilation and energy-optimisation strategies (16,17).

Further exploration of governance and policy alignment is also needed. IAQ data governance, transparency mechanisms, and campus-wide communication strategies can strengthen occupant awareness and promote responsible behaviours (15,27). Expanding the framework to incorporate emerging technologies—such as blockchain for secure data management or mobile sensing platforms for dynamic IAQ mapping—may also enhance its applicability in complex campus environments (11,17).

By integrating technological, analytical, and institutional components, the proposed conceptual framework provides a foundation for creating healthier, smarter, and more sustainable higher education environments.

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