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PAPER

Smart Campus Air Quality Monitoring: A Real-Time IoT Solution with React Native and Firebase Integration

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ABSTRACT

This study aimed to (1) design and develop an IoT-based hardware system for real-time air pollution monitoring, (2) develop an interactive mobile application for reporting and alert notifications, and (3) evaluate the system's spatial stability and data transmission performance. The proposed framework integrates Internet of Things (IoT) technology with cloud-based database architecture. The sensing node incorporates a SEN55 environmental sensor and an ESP32 microcontroller to collect key parameters, including PM2.5, VOC Index, and NOx Index. Sensor readings are processed using an edge aggregation algorithm to reduce signal noise before being stored in Firebase Realtime Database for real-time synchronization with the "React AQI" mobile application, developed using the React Native framework. The application supports multilingual visualization in Thai, English, and Chinese. Experimental results demonstrated a high average Data Delivery Ratio (DDR) of 94.76%, with data reliability ranging between 95.7% and 97.5%. A 20-day spatial comparative deployment conducted at Building 22 and Building 26 revealed consistent differentiation in pollution levels across locations, with a mean PM2.5 difference of 1.54 $\mu g/m^3$. The system effectively visualized pollution trends through interactive graphical analytics. These findings indicate that the proposed framework serves as an innovative prototype for Smart Health management within higher education institutions, aligned with the global Smart Campus paradigm.

KEYWORDS

smart campus, Internet of Things (IoT), edge computing, react native, real-time air quality monitoring, firebase realtime database, mobile visualization

1 INTRODUCTION

Air pollution remains one of the most critical environmental crises affecting global public health and quality of life. Fine particulate matter with a diameter of less than 2.5 micrometers (PM2.5) is particularly hazardous due to its ability to penetrate deep into the respiratory system and bloodstream, thereby increasing the risk of chronic diseases such as cardiovascular disorders and lung cancer [1]. The severity of this

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problem is especially pronounced in urban and densely populated areas characterized by intensive fuel combustion and traffic-related emissions [2].

Within the framework of higher education, the Smart University or Smart Campus paradigm has emerged as a strategic imperative for enhancing the quality of life within academic communities. Janpla and Nilsook [3] established an operational foundation centered on the convergence of digital ecosystems and the Internet of Things (IoT) to facilitate Smart Environment management and proactive health monitoring (Smart Living) on campus. Such IoT-driven health initiatives have gained significant academic traction; for instance, Nuanmeesri and Poomhiran [4] developed smart devices integrated with mobile applications for real-time vital sign monitoring, reflecting a broader trend toward sensor-driven individual health surveillance. In a similar vein, effective air quality management within university campuses necessitates high-resolution Spatial Monitoring to enable timely and evidence-based responses to pollution events.

Although governmental and private-sector air quality monitoring systems are widely available, they often face limitations in installation costs when attempting to achieve comprehensive spatial coverage across university campuses. Furthermore, many existing systems lack user-centered, real-time data communication interfaces accessible to the general public. In Thailand, prototype systems such as NMU-AQI [5] and IoT implementations using the Blynk Application [6] have demonstrated accurate sensor-based measurements. However, gaps remain in the development of highly interactive user interfaces and location-specific personalized alert mechanisms.

International literature likewise reports extensive efforts to develop low-cost air quality monitoring systems. Irawan et al. [7] highlighted the importance of IoT technologies in enabling automated data transmission without human intervention, thereby facilitating rapid governmental responses through real-time surveillance systems. Similarly, Dineshkumar et al. [8] focused on web-based visualization platforms, Jacob et al. [9] emphasized calibration accuracy, and Manikandan et al. [10] incorporated mobile-based notification systems. Nevertheless, limited research has integrated IoT sensing technologies with modern cross-platform application frameworks such as React Native to establish a fully synchronized data ecosystem connecting hardware devices, cloud databases, and end users under a modular system design approach.

In response to these research gaps, this study proposes and develops the "React AQI" system, an intelligent real-time air quality monitoring framework that integrates high-performance environmental sensors with an ESP32 microcontroller and synchronizes PM2.5, VOC Index, and NOx Index data via Firebase Realtime Database to a multilingual mobile application equipped with automated alert mechanisms. Beyond functioning as a measurement tool, the proposed system contributes to Smart Campus infrastructure by supporting data-driven decision-making for sustainable individual and community-level health protection.

2 RESEARCH OBJECTIVES

This study was conducted with the following objectives:

1. To design and develop a real-time IoT-based air quality monitoring system integrating the SEN55 environmental sensor with an ESP32 microcontroller for collecting PM2.5, VOC Index, and NOx Index data and synchronizing them to cloud-based database architecture.
2. To develop a cross-platform mobile application using the React Native framework for interactive visualization of air quality data through graphical analytics and

automated alert notifications when pollutant levels exceed predefined threshold standards.

3. To evaluate the system's performance in terms of data transmission efficiency and spatial stability of air pollution measurements across multiple deployment locations.

3 RESEARCH CONCEPTUAL FRAMEWORK

The development of the real-time air quality monitoring system, "React AQI," is founded upon the integration of three emerging technological domains: (1) Internet of Things, (2) cloud-based real-time database infrastructure, and (3) cross-platform mobile application development. This integrated architecture enables efficient acquisition, processing, synchronization, and visualization of environmental pollution data. The overall operational framework of the system is illustrated in Figure 1.

The framework components can be systematically categorized according to the sequential stages of data processing, as described below.

3.1 Data acquisition and edge processing layer

At the hardware layer, the system employs the SEN55 all-in-one environmental sensor, a high-performance sensing module capable of measuring key air quality indicators, including particulate matter (PM2.5), volatile organic compounds (VOC) index, nitrogen oxides (NOx) Index, temperature, and relative humidity. Raw sensor readings are transmitted via the I2C communication protocol to the ESP32 Maker Feather AIoT S3 microcontroller.

Edge computing techniques are implemented at the device level to enhance statistical stability and reduce communication overhead. Specifically, a minute-level averaging algorithm aggregates raw readings to attenuate signal noise before transmitting processed data to the cloud infrastructure. This edge aggregation mechanism improves data reliability while optimizing bandwidth utilization.

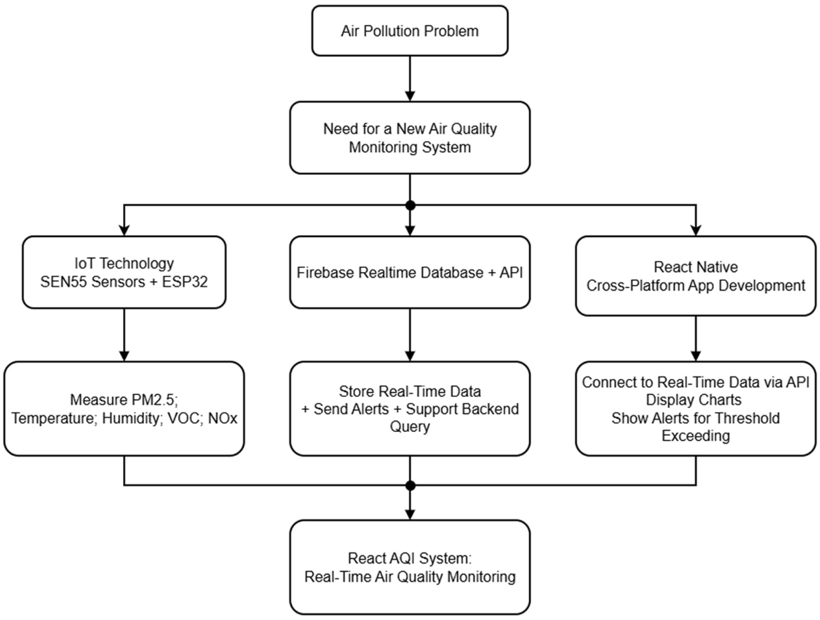

Fig. 1. Conceptual framework of the react AQI system

3.2 Cloud data management layer

The cloud infrastructure is implemented using Firebase Realtime Database, a NoSQL database platform that supports real-time data synchronization under an event-driven architecture. Processed air quality data are structured in JSON format, enabling low-latency communication between IoT devices and mobile applications while maintaining high system stability.

To ensure secure access and systematic data management, Firebase Authentication is integrated into the system architecture. This mechanism controls user-level permissions and enhances data security within the Smart Campus digital ecosystem.

3.3 Mobile visualization layer

The user interface layer is developed using the React Native framework, enabling cross-platform deployment on both iOS and Android operating systems. The mobile application incorporates the following core mechanisms:

- **Data integration:** Seamless connectivity with Firebase APIs to retrieve synchronized air quality data in real time through push-based updates.
- **Interactive visualization:** Dynamic trend charts generated using high-performance graphical libraries, allowing users to analyze temporal variations in pollutant concentrations across different time intervals.
- **Automated notification mechanism:** Context-aware alert generation when pollutant levels exceed predefined threshold standards.

This layer emphasizes usability, responsiveness, and accessibility, ensuring that environmental intelligence is communicated effectively to end users.

3.4 Analytical synthesis and system evaluation

All components will be analyzed and compared with established air quality standards to evaluate the system's performance in terms of measurement accuracy and notification responsiveness. These factors are considered fundamental to the development of a spatial air pollution monitoring system that supports health and well-being management within a smart university environment.

4 RESEARCH METHODOLOGY

This study adopted an engineering design process combined with an Agile system development cycle to enable iterative refinement based on empirical testing outcomes. The methodological framework was structured into three principal phases: (1) hardware design and development, (2) mobile application and cloud infrastructure development, and (3) field testing and performance evaluation.

4.1 Hardware design and air pollution sensing development

The system architecture follows a modular design principle to ensure robust scalability and future extensibility. The ESP32-S3 microcontroller was selected as the central processing unit, primarily for its integrated dual-mode wireless communication capabilities, high-speed computational power, and low-power consumption characteristics, which are essential for continuous environmental monitoring.

A critical component of the hardware layer is the integration of the Sensirion SEN55 intelligent environmental sensor. The selection of the SEN55 aligns with the technical framework established by Pietraru et al. [11], who emphasized the sensor's high stability and its on-chip humidity and temperature compensation mechanisms. These features are vital for maintaining high-precision measurements of PM1.0, PM2.5, PM10, VOC Index, and NOx Index, even within environments characterized by significant micro-climatic fluctuations. Furthermore, to ensure data integrity during high-frequency operation, the I2C communication bus was optimized using external 1kΩ pull-up resistors to mitigate potential signal instability, a technical necessity highlighted in contemporary IoT research to resolve voltage mismatch and ensure reliable data transfer between high-accuracy sensors and 32-bit microcontrollers.

To enhance communication efficiency and ensure data stability, edge computing techniques were implemented at the device level. A specialized data aggregation algorithm was designed to compute minute-level average values of environmental parameters before transmitting the structured JSON payloads to the cloud infrastructure. This edge-driven approach significantly reduced network transmission load and enhanced communication reliability by minimizing redundant data packets and filtering out short-term signal noise, thereby providing a more accurate representation of environmental trends for real-time mobile visualization.

4.2 Mobile application development and cloud infrastructure

The React AQI mobile application was developed using the React Native framework to provide an interactive cross-platform user interface compatible with both iOS and Android operating systems. The architecture prioritizes seamless real-time synchronization between IoT edge nodes and the end-user interface. This design integrates Google Firebase to ensure a responsive and robust solution for complex environmental health monitoring, consistent with the methodologies validated by Govoruhina and Nikiforova [12]. The technical implementation encompasses four primary domains:

- **Project architecture:** A component-based file structure was adopted to enhance software maintainability, modularity, and scalability.
- **Database integration:** Firebase Realtime Database was utilized for instantaneous data synchronization via WebSocket-based communication protocols. This architecture enabled real-time data updates without requiring manual screen refresh.
- **Navigation and user interaction:** React Navigation was implemented to manage application routing and screen transitions. Air quality index color-coding standards were integrated into the user interface design to provide intuitive risk communication through simplified visual cues.
- **Multilingual support:** The i18next framework was incorporated to support Thai, English, and Chinese languages, aligning with the international context of higher education institutions.

4.3 Field testing and system performance evaluation

The system was deployed in a real-world environment through field testing at Building 22 and Building 26 within the university campus over a continuous period of 20 days. The evaluation framework focused on the following performance indicators:

- **Data delivery ratio:** Assessed the stability and success rate of data transmission between the IoT device and the cloud infrastructure over the defined observation period.
- **Data reliability:** Evaluated the completeness and consistency of minute-level data samples stored in the database.
- **Spatial analysis:** Conducted a comparative analysis of daily average pollutant concentrations between the two deployment locations to examine sensor sensitivity and relative measurement accuracy under differing environmental conditions.

5 RESULTS

In the design and development of the smart air quality monitoring system, the study integrated IoT technology with cloud-based processing and a mobile application layer to enable efficient sensing, data transmission, and alert notification. The overall architecture of the React AQI ecosystem can be classified into three primary layers, as illustrated in Figure 2.

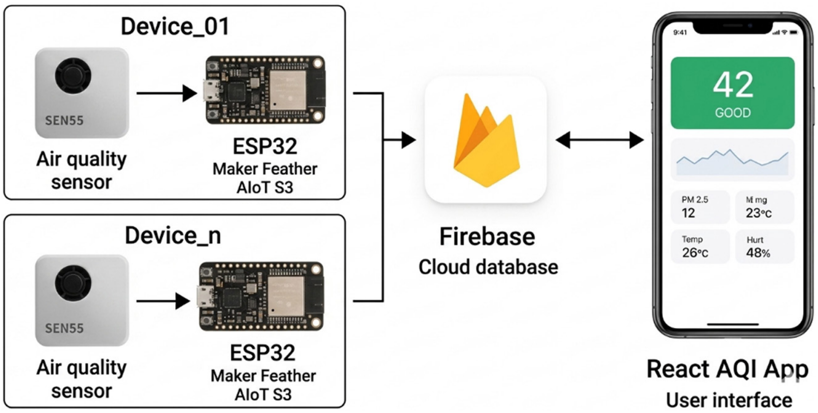

Fig. 2. High-level system architecture of the react AQI monitoring ecosystem

The architecture presented in Figure 2 demonstrates the end-to-end data flow, beginning from the Perception Layer (IoT sensing nodes deployed in Building 22 and Building 26), progressing to the Cloud Storage Layer (Firebase Realtime Database), and culminating in the Application Layer (mobile visualization and alert interface).

The implementation outcomes for each layer are described as follows.

5.1 Implementation results of IoT-based sensing nodes

This section describes the operational outcomes of the Perception Layer, focusing on the development of high-accuracy and stable IoT sensing nodes deployed under real-world environmental conditions to ensure data reliability prior to cloud transmission.

Hardware configuration and assembly. For the hardware development of the air quality monitoring device, a modular design approach was adopted. This approach enhances ease of maintenance, supports future system scalability, and improves digital signal stability. The structural configuration and device interconnections are described as follows.

- **Interconnection architecture:** The monitoring unit employs an ESP32 microcontroller (Maker Feather AIoT S3) as the main processing unit. It is interfaced with the SEN55 sensor via the I2C (Inter-Integrated Circuit) communication protocol using a Maker Port (SH1.0 4-pin) connector. This standardized connection minimizes electrical noise and prevents incorrect wiring through built-in polarity protection.
- **Pin assignment:** To ensure compatibility with the developed control software, the communication ports were assigned as follows:
  - **SDA (Serial Data):** Connected to pin D42 of the ESP32.
  - **SCL (Serial Clock):** Connected to pin D41 of the ESP32.
  - **VCC/GND:** A 5 V supply voltage from the control board is used to power the SEN55 sensor, ensuring optimal operation of its internal air intake fan.

  The interconnection between the ESP32 and the SEN55 sensor is illustrated in Figure 3.
- **Deployment setup:** The device was assembled in a compact configuration to ensure portability and structural stability. The SEN55 sensor was positioned in an airflow-optimized location, allowing unobstructed air circulation. This arrangement ensures accurate sampling and measurement of PM2.5, VOC, and NOx concentrations in accordance with the manufacturer's specifications.

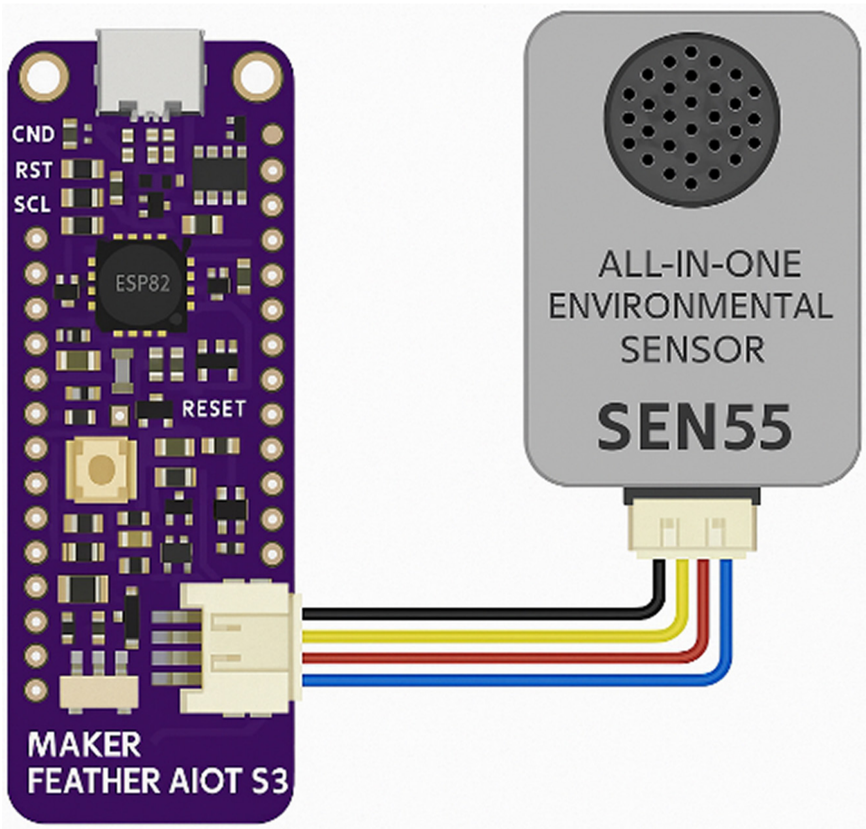

Fig. 3. Hardware integration of the IoT sensing node via I2C interface

This figure illustrates the seamless connection between the ESP32 microcontroller and the SEN55 sensor using the Maker Port for stable real-time data acquisition.

Microcontroller operational logic and edge processing algorithm. The ESP32 firmware was developed in C or C++ using the Arduino IDE, implementing an edge computing paradigm designed to enhance statistical robustness and minimize cloud processing overhead. The system's operational logic follows a structured pipeline from hardware initialization to cloud synchronization, as visually conceptualized in Figure 4.

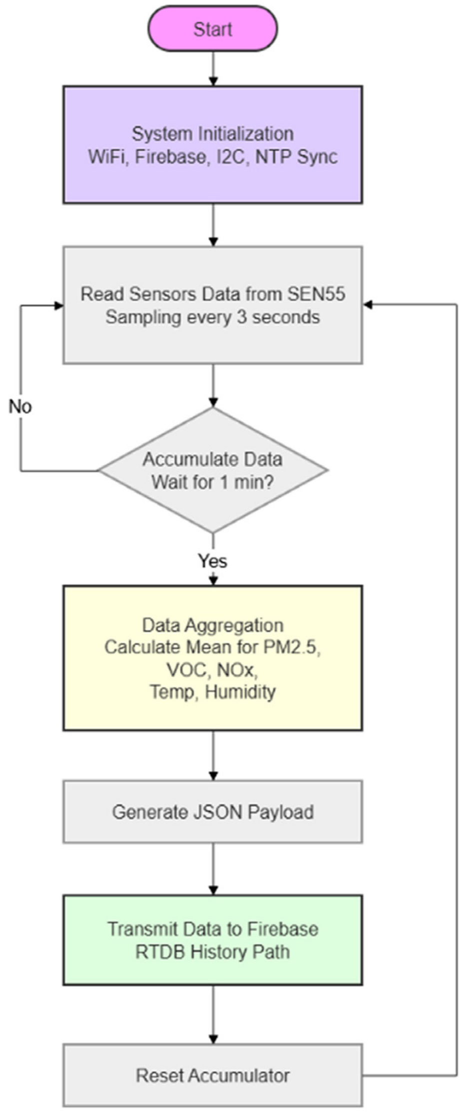

Fig. 4. IoT Node operational workflow and data pipeline

The core operational workflow, summarized in Figure 4, encompasses three primary stages:

1. **System initialization and time synchronization:** Upon startup, the ESP32 initialized the I2C interface and established wireless connectivity. Network Time Protocol (NTP) synchronization via pool.ntp.org was performed to ensure accurate timestamp assignment prior to cloud storage.

2. **High-frequency sampling and data accumulation:** To mitigate measurement deviations caused by signal noise, the algorithm was designed to perform sensor sampling at 3-second intervals. The data acquired from the SEN55 all-in-one sensor include PM2.5 concentration, VOC Index, NOx Index, temperature, and relative humidity. During this stage, raw values are stored in a temporary memory buffer within the ESP32's SRAM, acting as an edge data accumulator for real-time statistical processing.
3. **Data aggregation and cloud integration:** Following a 60-second duty cycle, the system performs an aggregation process by calculating the arithmetic means of all accumulated sensor metrics to derive stable representative indicators. The aggregated data are then encapsulated into a structured JSON payload and transmitted to the Firebase Realtime Database. This integration utilizes the Firebase_ESP_Client.h library via the HTTPS protocol, ensuring that the information displayed on the React Native application reflects high-fidelity averaged values synchronized in real time.

Cloud database schema design. To enable the "React AQI" system to support scalability and rapid data retrieval for visualization, this study designed a cloud database structure using Firebase Realtime Database based on a NoSQL model. The schema emphasizes a flat data relationship structure to reduce data access complexity and minimize latency.

The cloud storage architecture is organized in a hierarchical format to further enhance data accessibility and management efficiency, as illustrated in Figure 5.

Fig. 5. Hierarchical data structure and schema design in firebase realtime

Database. The figure illustrates the NoSQL organization of air quality data, including alert logs, device status, and user-defined location preferences for seamless real-time synchronization.

1. **Location-based alert management (alerts_by_location):** This structure is designed to store pollution events when measured values exceed predefined standard thresholds. The system supports internationalization (i18n) to facilitate multilingual alert notifications for international students and staff within the smart campus environment.

   An example of the corresponding JSON data structure is presented in Listing 1.

Listing 1: Example of Alert Event Data Structure in JSON Format

```
{
 “ALERT_1772602936_aqi_warning_DEVICE_02”: {
  “event_id”: “ALERT_1772602936_aqi_warning_DEVICE_02”,
  “severity”: “warning”,
  “message_i18n”: {
   “en”: “Air quality may start affecting health, especially sensitive groups.”,
   “th”: “คุณภาพอากาศเริมมีผลกระทบต่อสุขภาพ โดยเฉพาะกลุ่มเสียง”,
   “zh”: “空气质量开始影响健康，敏感人群需特别注意。”
  },
  “recommendation_i18n”: {
   “en”: “Reduce outdoor activity, close windows, and consider using an air purifier.”,
   “th”: “ลดกิจกรรมนอกอาคาร ปิดประตูหน้าต่าง และพิจารณาใช้เครื่องฟอกอากาศ”,
   “zh”: “减少户外活动，关闭门窗，并考虑使用空气净化器。”
  },
  “value_at_start”: 116,
  “threshold_value”: 101,
  “status”: “closed”
 }
}
```

   An examination of the data structure defined in Listing 1 indicates that the “React AQI” system is not merely designed to report numerical parameter values. Instead, it prioritizes interactive communication to enhance user experience through an adaptive content delivery mechanism. The React Native application dynamically retrieves data from the message_i18n and recommendation_i18n objects and automatically renders content according to the language locale configured on the user’s mobile device, supporting Thai, English, and Chinese.

   This data management strategy enables the system to deliver actionable insights, particularly through context-aware recommendations presented in a language that users fully comprehend. Such functionality contributes directly to reducing health risks associated with air pollution exposure. Consequently, this development approach demonstrates the effective application of interactive mobile technology to promote smart living within a digitally connected, culturally, and linguistically diverse university environment (Smart Campus).

2. **Device information and sensing logs:** This component functions as the central repository for both device metadata and minute-level air quality measurements (time-series data). The structure enables the system to continuously monitor device operational status and maintain historical pollution records for retrospective analysis.

The detailed data schema transmitted from the SEN55 sensor is presented in Listing 2.

Listing 2: JSON Structure for Device Metadata and Aggregated Sensing Data


```
"devices": {
  "DEVICE_01": {
    "history_1m": {
      "1770267254": {
        "avg_pm2p5": 80,
        "avg_voc_index": 3.25,
        "avg_nox_index": 0.05882,
        "avg_temperature": 27.3765,
        "avg_humidity": 56.2375,
        "sample_count": 20,
        "timestamp_text": "2026-02-05 11:54:14",
        "deviceId": "DEVICE_01",
        "locationId": "BUILDING_22"
      }
    }
  }
}
```


Based on the data structure defined in Listing 2, the system comprehensively integrates parameters that are critical for indoor environmental health assessment. The following academic and technical highlights should be emphasized:

- **Comprehensive sensing parameters:** In addition to PM2.5 concentrations, the system records VOC and NOx indices, which serve as important indicators of indoor chemical pollutants. These parameters are often overlooked in conventional air monitoring systems, thereby enhancing the analytical depth and environmental relevance of the proposed platform.
- **Statistical transparency:** The inclusion of the sample_count field (e.g., 20 samples per one-minute interval) reflects transparency in data quality assurance. It explicitly indicates that each reported value is derived from a sufficient number of samples in accordance with the high-frequency sampling algorithm described in Section "Microcontroller operational logic and edge processing algorithm".
- **Temporal and spatial context:** The tight integration of data with timestamp_text and locationId provides strong temporal and spatial contextualization. This structure facilitates future data analytics by enabling precise correlation analysis between time and location within the Smart Campus environment.

3. **Location-based latest data and user preferences:** This component is designed to support flexible data presentation based on user-centric design principles. The node stores the most recent parameter values (PM2.5, VOC, NOx, temperature, and humidity) to function as a data cache, enabling rapid dashboard loading and minimizing retrieval time.

   In addition, the system integrates with the Settings module in the React Native application, allowing users to designate a "Primary Device" according to their preferences. When accessing the Home Screen, the application automatically retrieves and prioritizes data from the location_latest node of the selected device.

   This mechanism enhances priority-based air quality monitoring at user-selected locations and significantly reduces data loading latency, thereby improving responsiveness and overall user experience.

5.2 Development of the mobile application user interface

Following the application layer of the proposed system architecture, the "React AQI" mobile application was developed using the React Native framework, with an emphasis on high interactivity and seamless cross-platform data visualization.

The application system consists of four principal functional modules, as described below.

Real-time dashboard and high-frequency data retrieval. On the main application interface under the "Location" menu (as illustrated in Figure 6), the system is designed to retrieve data from the latest node in the Firebase Realtime Database. This node is updated by the IoT device every three seconds.

This mechanism enables users within the university environment to monitor current air quality conditions with high accuracy and near real-time responsiveness.

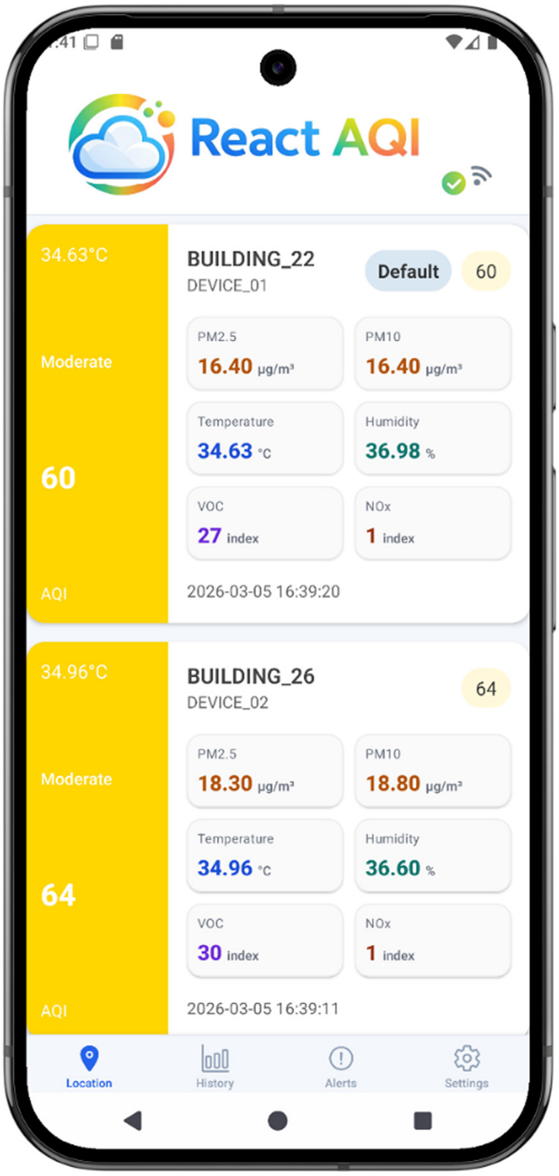

Fig. 6. Multi-location dashboard for real-time air quality monitoring

The application supports simultaneous visualization of multiple monitoring devices. In this project, data from two sensing nodes (Building 22 and Building 26) are displayed in a card-based interface, presenting PM2.5 values along with color-coded indicators based on established air quality standards.

In-Depth pollutant visualization. When users require more detailed information, they can navigate to the detailed display page (DeviceRealtimeScreen) by selecting a device entry on the main dashboard. The system employs a stack navigation mechanism to open a new interface (see Figure 7), while maintaining the same three-second data update frequency as implemented on the main screen.

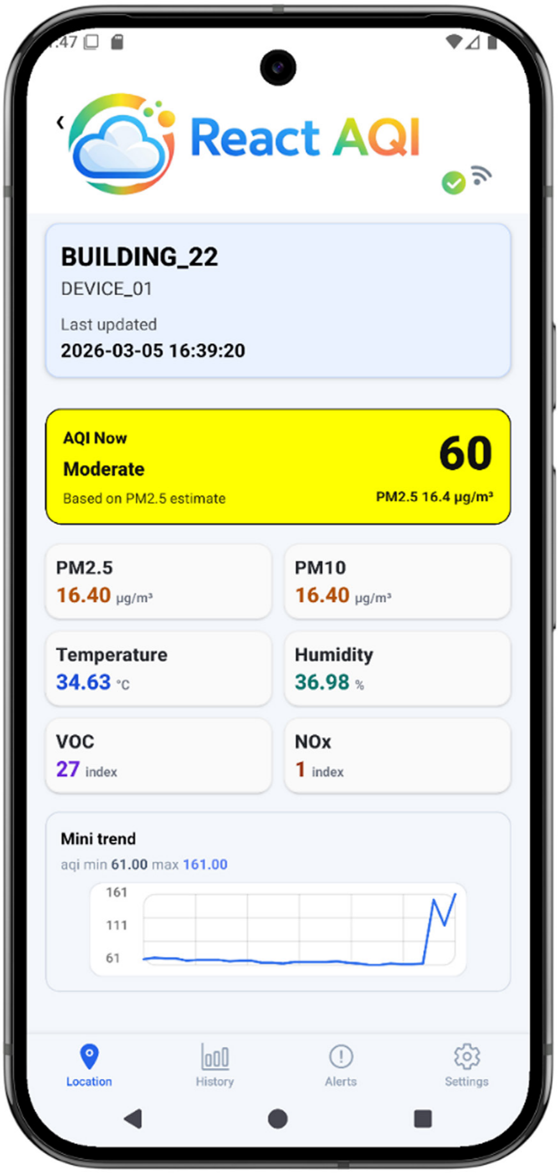

Fig. 7. Comprehensive pollutant analysis and detailed sensor metrics interface

This interface presents all parameters measured by the SEN55 sensor, including:

- **Mass concentration:** PM2.5 values (μg/m³).
- **Gas indices:** VOC Index and NOx Index, displayed in the form of intuitive gauges or clearly readable numerical indicators.
- **Environmental data:** Ambient temperature and relative humidity at the installation site.

Separating the in-depth visualization from the main dashboard reduces information complexity (data decluttering) while preserving full access to technical parameters for users who require detailed environmental analysis.

Historical data visualization and data management mechanism. The application incorporates a dedicated History Screen (see Figure 8) to enable users to perform detailed trend analysis of air quality conditions over time. The core functionality of this module lies in its integration with the history_1m node in the Firebase database, which is supported by an efficient data management mechanism as follows.

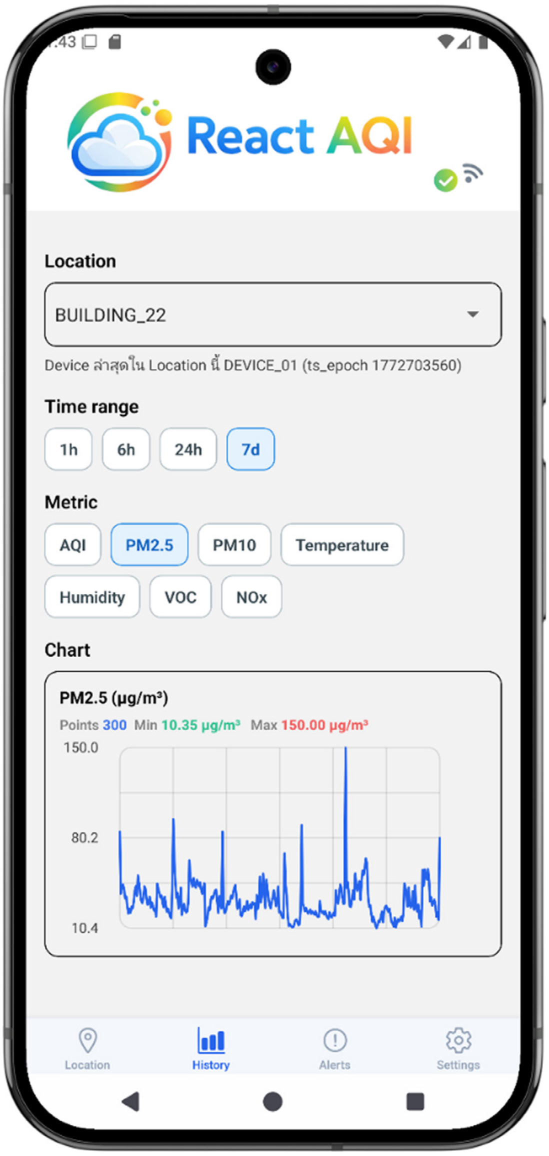

Fig. 8. Historical data analytics and trend visualization interface

1. **Data aggregation mechanism:** The data displayed in the graph are not raw sensor readings but are generated through an edge aggregation process performed on the ESP32 microcontroller. The system samples data from the sensor every three seconds and computes the mean value over a one-minute interval before transmitting the aggregated data payload to Firebase. This mechanism reduces signal noise-induced fluctuations and decreases network transmission overhead.
2. **Interactive analytical tools:**
   - **Location-based filtering:** Users can compare air quality data across different buildings (Building 22 and Building 26) to analyze spatial variations in environmental conditions.
   - **Scalable time range analysis:** The system supports multiple historical viewing intervals (1 hour, 6 hours, 24 hours, and 7 days). The application automatically retrieves data from the history_1m node and renders it as a line chart.
   - **Multi-metric analysis:** Users can switch between AQI, PM2.5, VOC, and NOx indicators, enabling the identification of correlations between campus activities and temporal variations in air pollution levels.

Intelligent alert management system. To enable the system to function as a complete surveillance tool, the application includes an Alerts Screen (as illustrated in Figure 9). This module aggregates pollution events that exceed predefined thresholds from the alerts_by_location database node and presents them as structured event logs. The key functionalities are described as follows.

1. **Advanced event filtering mechanism:** To support efficient data retrieval for both users and system administrators, three filtering dimensions are implemented.
   - **Metric:** Filters alerts based on indicator type (e.g., AQI, VOC, NOx).
   - **Severity:** Filters events according to severity level (e.g., Warning or Critical), enabling prioritization of response actions.
   - **Status:** Filters alert by event state (e.g., Open or Closed), distinguishing ongoing incidents from resolved events.
2. **Dynamic multilingual notification:** A key feature of the system is its ability to provide personalized and context-aware notifications. Alert messages and recommended actions displayed in the Alerts Screen are automatically adapted based on the user's selected language in the Settings module. The system supports Thai, English, and Chinese. This functionality is implemented through the retrieval of message_i18n and recommendation_i18n objects from Firebase, using the user-defined locale key. This ensures accurate risk communication and reduces language barriers across the university community.
3. **Detailed alert cards presentation:** Each alert entry is displayed in a structured card format containing comprehensive information, including device ID, affected location, peak pollution level, and multilingual recommended actions. This design enhances clarity and improves the effectiveness of critical risk communication.
4. **Real-time event synchronization:** When IoT nodes detect pollutant levels exceeding threshold values, the data are immediately pushed to the Alerts Screen. This enables the system not only to store historical events but also to function as a real-time air quality monitoring hub for the university environment.

Fig. 9. Multilingual alert interface supporting Thai, English, and Chinese user preferences

Note: Users can switch the display language between English and Thai via the Settings menu.

User preferences and application settings. To better accommodate diverse user requirements within the university environment, the application includes a Settings Screen (as illustrated in Figure 10), which allows users to customize system behavior according to their preferences. The main functions are described as follows.

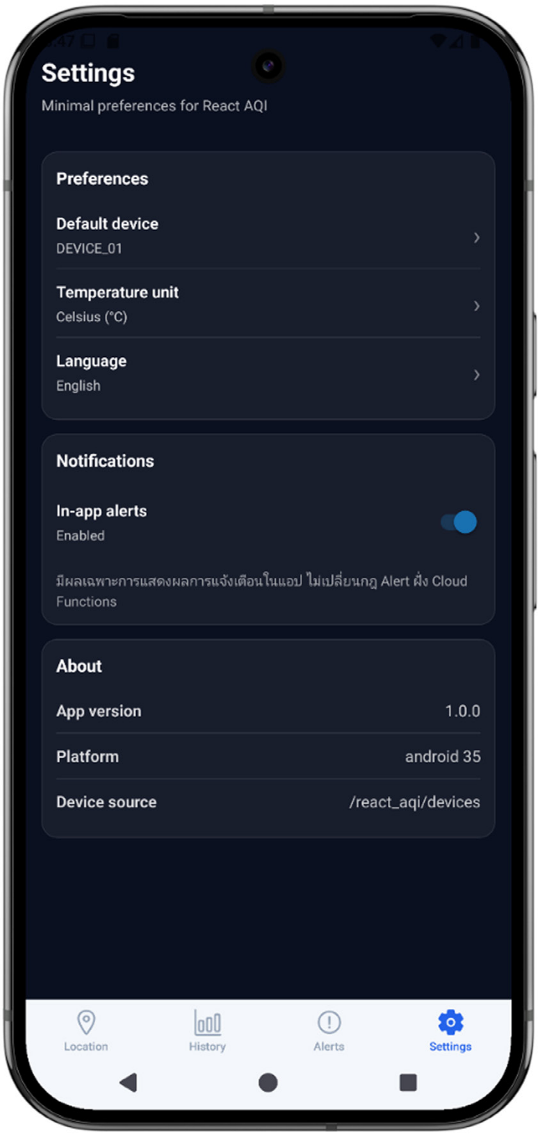

Fig. 10. User settings interface for personalized monitoring and multilingual configuration

1. **Default device selection:** Users can designate a "Primary Device" to be displayed first on the Dashboard (Location screen). This setting modifies the data retrieval priority from the location_latest node in Firebase, enabling faster access to frequently monitored locations.
2. **Multilingual preference management:** Users can select the preferred language for alerts and recommendation messages from three supported languages: Thai, English, and Chinese. The system maps the selected locale to the database's i18n fields to ensure accurate and consistent multilingual content rendering.
3. **User experience customization (UX customization):**
   - **Temperature unit:** Supports switching between Celsius (°C) and Fahrenheit (°F) to accommodate international users.
   - **In-app alerts control:** Users can enable or disable in-app notifications based on their preferences to reduce unnecessary interruptions.
4. **Application information:** The "About" section provides details regarding the application version and developer information, contributing to system transparency and credibility.

5.3 System efficiency and spatial analysis results

To ensure the performance reliability of the developed air quality monitoring system, continuous testing was conducted over a period of 20 days in real deployment environments located at Building 22 and Building 26. A total of 15,919 data records were collected and analyzed. The evaluation results are summarized as follows.

Data transmission efficiency. The communication performance between IoT nodes and the cloud database was evaluated using the data delivery ratio, particularly during peak usage hours (09:00–16:00). This period represents the most critical operating condition due to increased network traffic and frequent data updates. The results of the evaluation are presented in Table 1.

Table 1. Data delivery ratio analysis for 20-days monitoring period

Device ID	Installation Location	Expected Records	Actual Records Received	Data Delivery Ratio (DDR)
DEVICE_01	Building 22 (Zone A)	8,400	7,896	94.00%
DEVICE_02	Building 26 (Zone B)	8,400	8,023	95.51%
Average	System Overall	16,800	15,919	94.76%

The analysis indicates that the "React AQI" system achieved an average DDR of 94.76%. Notably, DEVICE_02 (Building 26) demonstrated the highest efficiency at 95.51%. The primary cause of incomplete transmission (i.e., DDR < 100%) was attributed to fluctuations in wireless network stability during peak usage periods within the university environment.

Nevertheless, a success rate exceeding 94% is considered "Excellent" for real-world deployment scenarios and is sufficient to support reliable air quality trend analysis.

Data integrity and stability. The stability of the edge processing algorithm was evaluated based on the sampling mechanism, which collects 20 samples per minute. Analysis of the sample_count field and statistical outputs revealed the following:

- **Data reliability:** The system achieved a sampling integrity ranging from 95.7% to 97.5%, indicating stable timing control and reliable execution of the ESP32-based firmware. This demonstrates that the microcontroller can maintain accurate temporal synchronization during continuous operation.
- **Statistical stability:** The standard deviation (SD) of PM2.5 values remained consistently within the range of 10.2–10.8 throughout the testing period. This confirms that the measurement process is stable and minimally affected by electrical noise or signal interference.

Spatial pollution trend analysis. To illustrate spatial variations in air quality, the average daily PM2.5 concentrations during peak hours (09:00–16:00) were compared across the two monitoring locations over the 20-day period, as shown in Table 2 and Figure 11.

Table 2. Comparison of daily average PM2.5 (μg/m³) between Building 22 and Building 26

Day	Date	Building 22 (Avg)	Building 26 (Avg)	Difference (Δ)
1	2026-02-05	45.45	44.40	−1.05
2	2026-02-06	32.12	34.50	+2.38
3	2026-02-09	28.50	31.20	+2.70
4	2026-02-10	30.15	32.45	+2.30
5	2026-02-11	27.88	30.12	+2.24
6	2026-02-12	31.40	33.55	+2.15
7	2026-02-13	29.25	31.10	+1.85
8	2026-02-16	33.60	35.80	+2.20
9	2026-02-17	35.10	37.45	+2.35
10	2026-02-18	32.05	33.90	+1.85
11	2026-02-19	28.75	30.40	+1.65
12	2026-02-20	26.40	28.15	+1.75
13	2026-02-23	25.10	27.20	+2.10
14	2026-02-24	29.35	31.05	+1.70
15	2026-02-25	31.80	33.50	+1.70
16	2026-03-02	27.25	28.95	+1.70
17	2026-03-03	25.40	28.15	+2.75
18	2026-03-04	22.15	24.60	+2.45
19	2026-03-05	29.80	32.35	+2.55
20	2026-03-06	32.91	35.43	+2.52
Mean	Overall	29.72	31.26	+1.54

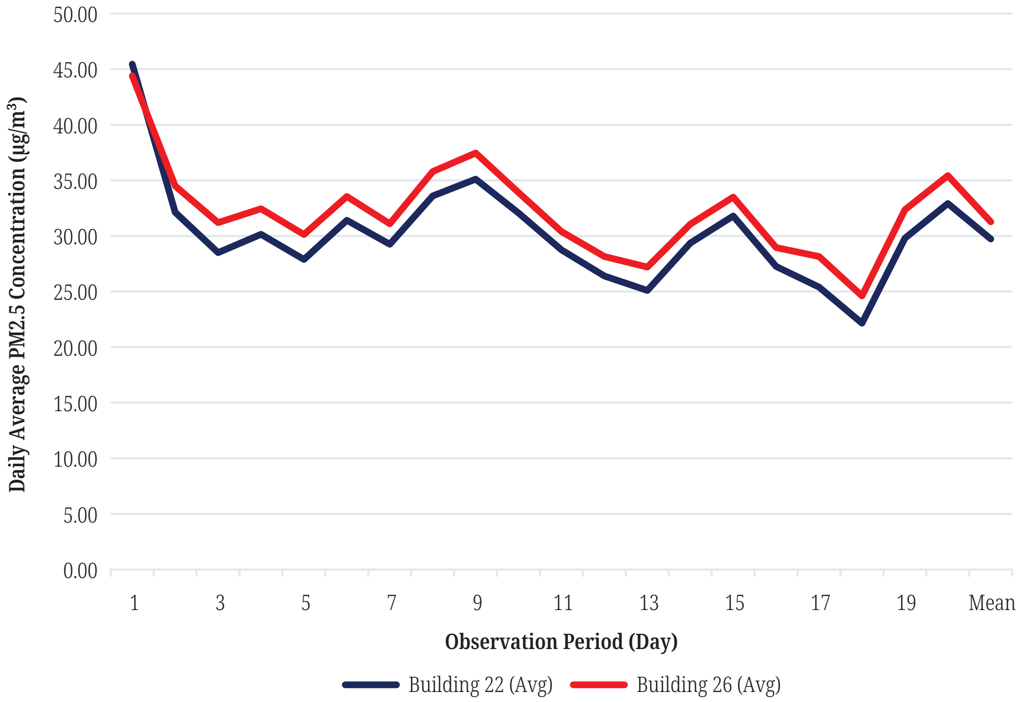

Fig. 11. Comparison of daily PM2.5 trends between Building 22 and Building 26

The spatial analysis results reveal several key findings as follows:

1. **Spatial consistency:** The data demonstrates that the sensor installed at Building 26 consistently recorded PM2.5 higher values than Building 22 throughout the testing period. The observed difference remained relatively stable within the range of 1.65–2.75 μg/m³. This confirms the system's spatial sensitivity in distinguishing environmental variations across different locations with high stability.
2. **System sensitivity:** The trend plots in Figure 11 indicate that both devices responded to changes in air pollution in a synchronized manner. This synchronized behavior confirms the high relative accuracy between the two SEN55 sensor units, despite being deployed at different locations.
3. **Statistical reliability:** The overall 20-day average values (29.72 μg/m³ and 31.26 μg/m³) are consistent with previously computed aggregate statistics, further reinforcing the long-term reliability and validity of the cloud-based data acquisition system.

6 DISCUSSION

From the development of the React AQI air quality monitoring system and performance testing within the university area, the researchers are able to discuss the research findings in several key aspects as follows:

6.1 Integration of IoT infrastructure and cloud platform

The observed DDR of 94.76% confirms that the adoption of Firebase Realtime Database as the cloud backbone enables robust and scalable real-world deployment within a university environment. This finding aligns with Chaarmart et al. [13], who identified Firebase as a reliable cloud infrastructure for environmental IoT systems. However, the React AQI framework extends prior implementations by incorporating:

- **High-frequency data synchronization:** Achieving a 3-second sensing interval with minute-level data aggregation for granular temporal analysis.
- **Event-driven multilingual alert architecture:** Utilizing cloud-based triggers to deliver localized notifications based on predefined air quality thresholds.
- **Cross-platform mobile accessibility:** Leveraging React Native to provide seamless user experiences across iOS and Android without institutional server dependency.

When compared with Tipaksorn et al. [14], who implemented MQTT over a private cloud infrastructure, the present architecture offers enhanced accessibility and significantly reduced maintenance overhead. The edge-to-cloud model employed in this study demonstrates architectural efficiency comparable to distributed IoT systems reported by Pilania and Kumar [15], particularly in handling high-velocity environmental sensing data.

Crucially, the success of the HTTPS-based lightweight JSON transmission protocol used in this framework is supported by the findings of Ibrahim et al. [16]. Their research demonstrates that HTTP POST requests offer exceptional outperformance for second-by-second sensor data transfer, providing a simpler yet highly efficient integration between Wi-Fi-enabled microcontrollers and central processors compared to traditional MQTT or TCP/IP setups. Furthermore, the technical reliability of the sensing node was enhanced by addressing I2C communication stability. As noted by Ibrahim et al. [16], the absence of internal pull-up resistors in modern 32-bit microcontrollers can lead to unstable data transfer from high-accuracy sensors like the SEN55; thus, the implementation of external 1kΩ pull-up resistors was vital to maintaining data integrity under continuous operation.

The maintenance of a DDR above 94% under real-world wireless network variability indicates that RESTful API communication combined with edge aggregation is sufficient for campus-scale deployment. This architecture effectively bypasses the need for specialized, complex IoT communication frameworks while ensuring the low latency required for interactive mobile health applications. without requiring specialized IoT communication frameworks.

6.2 Accuracy and spatial pollution sensitivity

The system consistently detected PM2.5 differentials between Building 22 and Building 26, with an average spatial variation of 1.54 μg/m³ over the 20-day monitoring period. The synchronized fluctuation trends between both sensing nodes indicate high relative sensor accuracy and stable calibration performance.

These findings reinforce the conclusions of Kaewkhun and Sakunkoo [17] regarding the reliability of low-cost sensors for field-based environmental monitoring. Furthermore, the Data Reliability rate of up to 97.5% confirms that the implemented edge-processing algorithm effectively mitigates signal noise and preserves sampling integrity.

The inclusion of multi-parameter sensing (PM, VOC, NOx) reflects a multi-sensor data fusion perspective consistent with Techakijkachorn et al. [18], enabling a more comprehensive interpretation of indoor and semi-outdoor environmental conditions.

Importantly, the demonstrated spatial sensitivity suggests that React AQI is capable of supporting micro-zoning environmental policy within smart campus ecosystems, where localized ventilation strategies and exposure risk assessments are required.

6.3 Innovation in visualization and global accessibility

From an application-layer perspective, the React AQI implementation addresses limitations observed in prior mobile-based air monitoring systems, such as those reported by Wahyuni et al. [19], where automated alerting and spatial comparison features were limited.

React AQI introduces:

- **Intelligent alert management** with severity-based filtering.
- **Spatiotemporal Analytics** integrated with real-time dashboards for trend visualization.
- **Multilingual adaptive essaging** (Thai, English, Chinese) embedded directly within the cloud schema to support internationalized academic environments.

The system transitions from a passive reporting dashboard to an interactive decision-support platform. This design strategy aligns with the findings of

Mathews et al. [20], which emphasize that intuitive, context-specific visualization is fundamental to reducing knowledge barriers and fostering proactive environmental health decisions. By delivering context-aware recommendations through an accessible cross-platform framework, React AQI significantly strengthens the technological infrastructure required for Smart Campus sustainability and inclusive well-being.

7 CONCLUSION AND FUTURE WORK

This study successfully developed and evaluated the performance of the "React AQI" system, an intelligent air quality monitoring system based on IoT technology designed for a Smart Campus environment. The findings can be summarized according to the research objectives as follows:

1. **Internet of Things sensing node development (hardware development):** The researchers designed and implemented an air pollution sensing unit using an ESP32 microcontroller integrated with the SEN55 sensor. The system is capable of accurately measuring PM2.5, VOC Index, and NOx Index. An edge processing mechanism was employed to handle high-frequency data locally prior to cloud transmission. This approach reduces network workload and enhances data transmission stability and storage efficiency.
2. **Mobile application interactivity development:** The "React AQI" mobile application, developed using the React Native framework, successfully integrates real-time data from the Firebase Realtime Database and presents it through an interactive user interface (UI), including trend graphs and an automated alert system. The support for three languages (Thai, English, and Chinese) helps eliminate communication barriers regarding air pollution information within a culturally diverse university community, aligning with the internationalization goals of higher education institutions.
3. **System efficiency and spatial analysis:** Continuous real-world testing over a 20-day period at Building 22 and Building 26 confirmed the system's performance, achieving an average Data Delivery Rate (DDR) of 94.76% and a data reliability of 97.5%. Furthermore, the system demonstrated high spatial sensitivity, consistently and accurately distinguishing variations in pollution levels across different sensor deployment locations.

Future work

Future research directions include:

- Integration of artificial intelligence models for predictive air quality forecasting.
- Expansion to distributed multi-campus or community-scale deployment.
- Incorporation of GIS-based spatial heat mapping.
- Energy-efficient node optimization (e.g., solar-assisted or battery-managed systems).
- Development of big data analytics frameworks to support institutional environmental policy planning.

The integration of predictive analytics and adaptive threshold learning mechanisms may further enhance proactive environmental risk mitigation within smart urban ecosystems.

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9 DECLARATION OF GENERATIVE ARTIFICIAL INTELLIGENCE AND ARTIFICIAL INTELLIGENCE ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the author used Gemini in order to refine the academic language, improve the readability of the manuscript, and generate technical illustrative diagrams. After using this service, the author reviewed and edited the content as needed to ensure technical accuracy according to the research design and takes full responsibility for the content of the publication.

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