

การพัฒนาระบบตรวจวัดคุณภาพอากาศและแจ้งเตือนฝุ่น PM2.5 แบบเรียลไทม์
โดยประยุกต์ใช้เทคโนโลยีอินเทอร์เน็ตของสรรพสิ่ง
The Development of a Real-Time Air Quality Monitoring and PM2.5 Alert System
Using Internet of Things Technology

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บทคัดย่อ

งานวิจัยนี้มีวัตถุประสงค์เพื่อพัฒนาระบบตรวจวัดคุณภาพอากาศและแจ้งเตือนฝุ่น PM2.5 แบบเรียลไทม์โดยใช้เทคโนโลยีอินเทอร์เน็ตของสรรพสิ่ง ประเมินประสิทธิภาพของระบบ และประเมินการยอมรับของผู้ใช้งาน การวิจัยดำเนินการตามรูปแบบการวิจัยและพัฒนา ระบบที่พัฒนาขึ้นประกอบด้วย 3 ส่วน ได้แก่ สถานีตรวจวัดคุณภาพอากาศภายนอกอาคาร ระบบประมวลผลและจัดเก็บข้อมูลบนคลาวด์ และส่วนแสดงผลพร้อมระบบแจ้งเตือนผู้ใช้งาน สถานีตรวจวัดใช้พลังงานแสงอาทิตย์ร่วมกับแบตเตอรี่สำรอง สามารถทำงานกลางแจ้งได้อย่างต่อเนื่อง โดยตรวจวัดข้อมูล PM2.5 และอุณหภูมิ แล้วส่งข้อมูลผ่านเกตเวย์ IoT ด้วยเครือข่าย 4G ไปยังระบบคลาวด์โดยใช้โพรโทคอล MQTT ข้อมูลถูกแสดงผลผ่านเว็บแดชบอร์ดป้าย LED ณ จุดติดตั้ง และแจ้งเตือนผ่านแอปพลิเคชันเทเลแกรม เมื่อค่าฝุ่น PM2.5 เกินเกณฑ์ที่กำหนด การประเมินประสิทธิภาพใช้การทดสอบแบบแบล็กบ็อกซ์และการประเมินค่าความคลาดเคลื่อน ผลการทดสอบพบว่ารายการทดสอบทั้ง 10 รายการผ่านเกณฑ์ทั้งหมด ครอบคลุมการตรวจวัด การส่งข้อมูล การประมวลผล การแสดงผล การแจ้งเตือน การจำแนก ระดับความเสี่ยง และการทำงานโดยรวมของระบบ การเปรียบเทียบค่าการตรวจวัดของระบบ AQMS กับอุปกรณ์ IQAir AirVisual ซึ่งเป็นอุปกรณ์ตรวจวัดเชิงพาณิชย์ โดยใช้ข้อมูลรายชั่วโมงที่จับคู่ตามเวลาได้จำนวน 720 คู่ จากระยะเวลา 30 วัน พบว่ามีค่าความคลาดเคลื่อนร้อยละสัมบูรณ์เฉลี่ยร้อยละ 7.72 ค่าความคลาดเคลื่อนสัมบูรณ์เฉลี่ย 1.65 ไมโครกรัมต่อลูกบาศก์เมตร และค่ารากของความคลาดเคลื่อนกำลังสองเฉลี่ย 1.96 ไมโครกรัมต่อลูกบาศก์เมตร ผลดังกล่าวสะท้อนว่าค่าการตรวจวัดจากอุปกรณ์ทั้งสองมีความสอดคล้องกันภายใต้พื้นที่ ช่วงเวลา และสภาพแวดล้อมที่ศึกษา ทั้งนี้ ผลการเปรียบเทียบไม่ถือเป็นการยืนยันความแม่นยำเชิงมาตรวิทยาของระบบ เนื่องจากไม่ได้สอบเทียบกับเครื่องมือมาตรฐาน FRM/FEM การประเมินการยอมรับจากกลุ่มตัวอย่าง 30 คน พบว่าผู้ใช้งานมีการยอมรับระบบโดยรวมอยู่ในระดับมากที่สุด มีค่าเฉลี่ยโดยรวม 4.51 และส่วนเบี่ยงเบนมาตรฐาน 0.51 ผลการศึกษาสะท้อนว่าระบบสามารถทำงานตามฟังก์ชันที่กำหนด และให้ค่าการตรวจวัดที่มีความสอดคล้องกับอุปกรณ์เปรียบเทียบกับเงื่อนไขของการศึกษานี้ อย่างไรก็ตาม ควรมีการสอบเทียบกับเครื่องมือมาตรฐาน การทดสอบระยะยาว และการประเมินกับผู้ใช้จำนวนมากขึ้นก่อนนำไปใช้งานในวงกว้าง

คำสำคัญ: ฝุ่นละอองในอากาศ PM2.5, ระบบแบบเรียลไทม์, การตรวจวัดคุณภาพอากาศ, อินเทอร์เน็ตของสรรพสิ่ง, ระบบแจ้งเตือน

Abstract

This research aimed to develop a real-time air quality monitoring and PM2.5 alert system using Internet of Things technology, evaluate the system's performance, and assess user acceptance. The study followed a research-and-development approach. The developed system consisted of three main components: an outdoor air quality monitoring station, a cloud-based data processing and storage system, and a display and user notification module. The monitoring station was powered by solar energy with

backup batteries and was capable of continuous outdoor operation. It measured PM_{2.5} and temperature and transmitted the data through an IoT gateway over a 4G network to the cloud system using the MQTT protocol. The data were displayed through a web dashboard and an on-site LED display, while notifications were sent via Telegram when PM_{2.5} levels exceeded the specified thresholds. System performance was evaluated using black-box testing and error assessment. All ten test items passed, covering measurement, data transmission, processing, display, notification, risk-level classification, and overall system operation. Measurement agreement was evaluated using 720 time-aligned paired hourly observations collected over 30 days from the AQMS and an IQAir AirVisual commercial monitor. The comparison yielded a Mean Absolute Percentage Error of 7.72%, a Mean Absolute Error of 1.65 $\mu\text{g}/\text{m}^3$, and a Root Mean Squared Error of 1.96 $\mu\text{g}/\text{m}^3$. These results indicated agreement between the measurements from the two devices under the study location, period, and environmental conditions. However, the comparison did not confirm the system's metrological accuracy because it was not calibrated against an FRM/FEM standard instrument. The user acceptance evaluation was conducted with 30 participants, and overall acceptance was at the highest level, with a mean of 4.51 and a standard deviation of 0.51. The findings indicate that the system performed the predefined functions and produced measurements consistent with those of the comparison device under the conditions of this study. However, calibration against a standard instrument, long-term testing, and evaluation with a larger user sample should be conducted before wider deployment.

Keywords: PM_{2.5}, Real-time system, Air quality monitoring, Internet of things (IoT), Alert system

1. Introduction

Air pollution is the contamination of air by substances or objects that are harmful to health and the environment. It has many sources, such as fuel combustion, industrial emissions, and the burning of agricultural residues. Air pollution is an environmental problem that severely and continuously affects public health and quality of life (Chang et al., 2023; Jindawet, 2023). PM_{2.5}, or fine particulate matter, is defined as particles with a diameter of no more than 2.5 microns (U.S. Environmental Protection Agency, 2026; World Health Organization, 2021). These suspended particles disperse in the atmosphere and may exist in liquid or solid form. They can penetrate the respiratory system and bloodstream, which may result in respiratory and cardiovascular diseases and increase morbidity and premature mortality. The impacts of air pollution are not limited to health; they also significantly affect the economy and society (Li et al., 2022; Manisalidis et al., 2020). Consequences include increased healthcare costs, reduced labor productivity, and negative effects on tourism and agriculture. In the long term, this problem may contribute to social inequality and reduce the overall quality of life of the population.

In Thailand, PM_{2.5} levels are high across many areas, especially during the winter season. During this period, temperature inversions often occur, leading to the accumulation of particulate matter near the ground. In particular, PM_{2.5} levels in Phetchaburi Province have generally increased (Pollution Control Department, 2023). Additionally, agricultural burning is frequently observed and contributes to higher pollution levels. Statistics on PM_{2.5} from November 2024 to March 2025 indicated concentrations exceeding 75 micrograms per cubic meter ($\mu\text{g}/\text{m}^3$) (Division of Health Impact Assessment, Department of Health, 2026). As a result, public health may be adversely affected. Notably, children, pregnant women, older adults, and people with underlying diseases are more sensitive to air pollution exposure than the general population. Currently, information and communication technology, especially the Internet of Things (IoT), plays an important role in monitoring and alerting by speeding up response times and improving monitoring efficiency. Specifically, a mobile application alert system can deliver timely warnings when important events

occur, ensuring that stakeholders are immediately informed. In addition, a web dashboard can consolidate warning information on a single screen, streamlining situation monitoring and facilitating quicker decision-making. Given these benefits, improved data accessibility, faster response, and greater monitoring efficiency, these approaches have strong potential to help address this problem.

Previous studies have demonstrated the feasibility of integrating particulate-matter sensors, Internet of Things technology, and mobile notification services for PM_{2.5} monitoring. However, several limitations remain for site-specific outdoor deployment, including dependence on local Wi-Fi infrastructure; limited integration of outdoor monitoring, cloud-based processing, public display, and automated notification functions; and insufficient reporting of measurement agreement based on extended paired outdoor observations. In addition, province- or region-level air quality services may not adequately represent PM_{2.5} conditions at a specific installation site. To address these gaps, this study developed a solar-powered outdoor PM_{2.5} monitoring system that uses RS485 communication, a 4G cellular gateway, MQTT-based cloud transmission, a web dashboard, an on-site LED display, and automated Telegram notifications. The system was functionally verified, its measurements were compared with simultaneous measurements from a commercial comparison monitor, and descriptive user feedback was collected through a pilot user acceptance evaluation.

Therefore, this research aimed to develop a real-time air quality monitoring and PM_{2.5} alert system using Internet of Things technology; verify the predefined system functions; evaluate measurement agreement between the developed AQMS and a commercial IQAir AirVisual monitor under the study conditions; and obtain descriptive feedback through a pilot user acceptance evaluation. The developed system was intended to support site-specific PM_{2.5} surveillance, environmental risk communication, and local decision-making.

2. Materials and Methods

This study was conducted as a research and development project. The objectives were to develop a real-time air quality monitoring and PM_{2.5} alert system, evaluate its performance, and assess user acceptance of the system when particulate matter levels were high enough to have immediate health effects. The research procedure was divided into four stages, as follows.

2.1 Study of problems, theories, and related research

In this study, the researchers systematically examined the problem and reviewed concepts, theories, documents, and related research to establish a knowledge base for the analysis, design, and development of a real-time air quality monitoring and PM_{2.5} alert system. The details are as follows.

2.1.1 Study of the PM_{2.5} problem

The researchers studied air pollution, focusing on particulate matter with a diameter of no more than 2.5 microns (PM_{2.5}). PM_{2.5} is an air pollutant that affects public health and environmental quality. The researchers considered major sources of air pollution, such as vehicle emissions, industrial facilities, open agricultural burning, wildfires, transportation, dust, and black smoke. Climatic factors and the area's geographical characteristics were also examined because these factors can contribute to the accumulation of particulate matter in the atmosphere, especially in winter. During this season, the ground is often cooler than the upper atmosphere, and this temperature difference can cause a temperature inversion. The inversion acts as a dome, trapping particulate matter and keeping unusually high levels of particulate matter near the ground (Bilal et al., 2022; Serttikul et al., 2023). The researchers reviewed PM_{2.5} data in Phetchaburi Province and found that concentrations tended to increase (Pollution Control Department, 2023). From November 2024 to March 2025, PM_{2.5} concentrations exceeded 75 micrograms

per cubic meter ($\mu\text{g}/\text{m}^3$) (Division of Health Impact Assessment, Department of Health, 2026). This period often coincides with agricultural burning and weather conditions that favor pollution accumulation. At times, air quality reached levels that can affect public health. Children, pregnant women, older adults, and individuals with chronic illnesses are particularly vulnerable to air pollution because they are more sensitive than the general population.

2.1.2 Study of standards and alert criteria

In this study, the researchers reviewed air quality standards and PM2.5 assessment criteria from academic documents and relevant agencies. Based on this review, Thailand's air quality index, developed by the Pollution Control Department (Pollution Control Department, 2023) was used as a guideline for surveillance levels, risk assessment, and user notification. The index is divided into five levels, with color-coded warnings that are easy to interpret and effective for communicating with users, as shown in Table 1.

This study also covered practical approaches to classifying air quality levels for warning purposes, using an index that defines categories such as good air quality, levels beginning to affect health, and hazardous levels. The index provided clear criteria for setting conditions in the data processing system, generating alert messages, and designing communication formats that matched the severity of the situation. In the developed system, the researchers applied this index to guide alert generation within the application.

Table 1. Concentration values of air pollutants for the air quality index

PM2.5 ($\mu\text{g}/\text{m}^3$)	Air Quality Level	Color
0 – 15.0	Very Good	Blue
15.1 – 25.0	Good	Green
25.1 – 37.5	Moderate	Yellow
37.6 – 75.0	Beginning to have health effects	Orange
≥ 75.1	Has health effects	Red

2.1.3 Study of IoT technology and related systems

The researchers examined principles, concepts, and technologies related to the Internet of Things (IoT), focusing on their application to real-time air quality monitoring. They outlined how each key system component contributes to this purpose (Bacquet et al., 2022). Monitoring devices and air quality sensors detect pollutant levels; preliminary processing systems prepare sensor data; data communication devices and transmission networks relay information; cloud systems provide data storage and processing; and user interfaces display results and trigger notifications.

The researchers evaluated the feasibility of a continuously operating, solar-powered outdoor air quality monitoring station. The station consisted of solar panels, which convert sunlight into electricity; a charge controller, which regulates battery charging; backup batteries, which store energy for periods without sunlight; and a voltage converter, which adjusts the voltage for device compatibility. PM2.5 sensors, which measure fine particulate matter in the air; signal conversion devices, which transform sensor outputs into digital signals; and a gateway, which transmits data to the online system, enabled data collection and transmission. Studying these components supported the design of an outdoor monitoring system with solar power, backup energy storage, and field data transmission capabilities.

In addition, the researchers studied the cloud-based data storage system and the web dashboard system to define the data flow from the monitoring point to the display point. On this basis, the

research emphasized the need for permanent data storage, rapid data processing, and data presentation in easily interpretable forms (Sahin & Ifenthaler, 2021), including graphical representations, statistics, and maps showing the locations of monitoring stations. The comparison processes for sensors and monitoring devices were also described to ensure the accuracy and reliability of real-time PM_{2.5} monitoring data. In addition, previous studies have used a range of approaches for communication, data sources, and notifications for PM_{2.5} monitoring. Phonrit et al. (2020) developed a particulate matter monitoring system using smartphones with sensors connected to a network. Pongphab & Santakij (2021) combined PM_{2.5} monitoring with notifications via the LINE application, while Tantatsanawong (2026) created an air-pollution alert system based on air-quality data from an external API rather than measurements collected directly at the installation site. AlAwadhi and Dashti (2021) discussed Telegram as a platform for information sharing. These studies demonstrated the feasibility of sensor-based monitoring and mobile notifications, but they differed in communication infrastructure, data sources, and display functions. For the present study, a 4G cellular gateway was chosen as a context-specific solution for an outdoor installation site where fixed Wi-Fi infrastructure was not reliably available. The developed system combined outdoor measurements, cloud-based storage, a web dashboard, an on-site LED display, and automated Telegram notifications.

2.1.4 Synthesis of the conceptual framework for system development

After studying the problem, air quality standards, and related technologies, the researchers synthesized findings from the literature and related research to develop a conceptual framework for a real-time air quality monitoring and PM_{2.5} alert system. Based on this framework, the system was defined as consisting of three main components: an air quality data monitoring component that collects and transmits air quality information; a cloud-based data processing and storage component that analyzes and stores the collected data; and a user display and alert component that presents air quality data and sends alerts to users.

In this conceptual framework, PM_{2.5} sensors collect data along with weather-related variables and transmit them via a 4G network to a cloud server. The server stores, analyzes, and processes the data. The system displays the processed results in real time on a web dashboard. If air quality exceeds the specified criteria, the system immediately generates and transmits alert messages to users via the application, notifying them of the associated risk, as shown in Figure 1. This process aligns with the system framework presented in the article and integrates air quality monitoring technology, data communication, and information systems to support environmental risk communication.

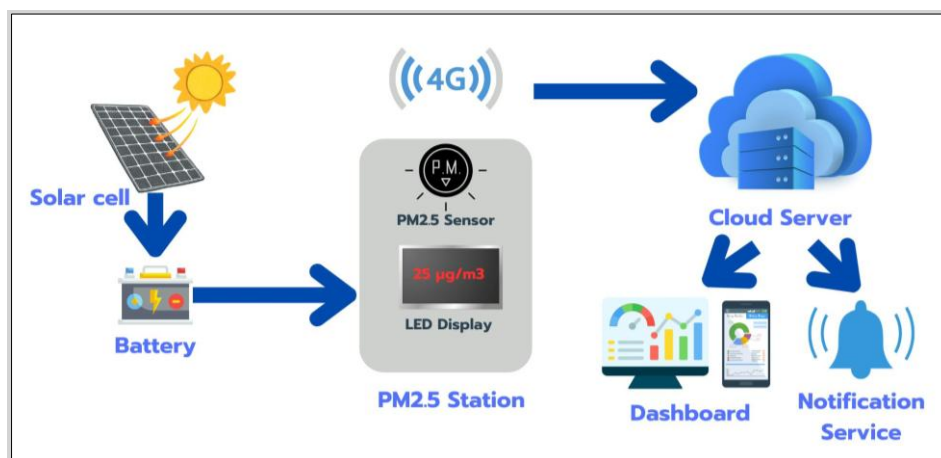


Figure 1. System concept framework

2.2 System analysis, design, and development

After conducting a comprehensive problem analysis and reviewing the relevant literature, the researchers systematically defined the system requirements, designed the operational architecture, and implemented a real-time air quality monitoring and PM2.5 alert system. The system continuously provides reliable measurements, processing, visualization, and alerts for practical outdoor applications. It integrates monitoring station modules, data communication interfaces, cloud-based processing and storage units, and user display and notification modules into a cohesive framework.

2.2.1 System Requirements Analysis

The researchers analyzed system requirements based on the nature of the problem and the actual context of use. The system was required to continuously monitor PM2.5 concentrations and related weather variables in an outdoor environment, use a power source suitable for the installation area, transmit data from the monitoring point to the central system in real time, present information in a form that users could easily understand, and automatically send alert messages when air quality values exceeded predefined thresholds. This analysis led to the definition of the main system components: the air quality monitoring station, the data storage and processing system, the web dashboard, and the application-based alert system.

2.2.2 System architecture design

In designing the system, the researchers defined its architecture as consisting of three main components: 1) the air quality monitoring station, 2) cloud-based data processing and storage, and 3) a user web dashboard with alert notifications. The workflow progressed as follows: solar energy powered the monitoring station, which collected PM2.5 measurements. A 4G network was used to send sensor data to the cloud server for processing, storage, and analysis. The processed data were then presented on the web dashboard. If monitored values exceeded the thresholds, alert notifications were sent to users via Telegram. This sequence efficiently connected data from monitoring points to end users, exemplifying an integrated hardware–software system design based on the conceptual framework in Section 2.1.4.

2.2.3 Design and development of the air quality monitoring station

The Renke RS-BYH-M-EX monitoring unit was selected because it is designed for outdoor installation, has the necessary PM2.5 measurement range, and supports RS485 Modbus RTU communication. The Protoss-PG41 gateway was selected because it can receive RS485 data directly and transmit them over a 4G cellular network, eliminating the need for a separate microcontroller. The researchers chose RS485 Modbus RTU because it is compatible with the monitoring unit and the industrial gateway and is suitable for wired communication in outdoor installations. A 4G cellular connection was selected because the fixed Wi-Fi infrastructure at the installation site was unreliable. MQTT was selected because it supports lightweight publish–subscribe messaging, which is well suited to the transmission of IoT data. Telegram notifications were selected because they enabled automated group notifications within the existing server environment without requiring the researchers to develop and maintain a dedicated mobile application. A 100 W solar panel and two 12 V, 20 Ah batteries were selected to support outdoor operation during periods of limited grid-power availability and reduced sunlight, as shown in Table 2.

Table 2. Hardware and communication specifications of the developed system

Component	Model/Specification	Main Function
Air quality monitoring unit	Renke RS-BYH-M-EX	Measures PM _{2.5} and temperature
PM _{2.5} measurement principle	Laser light scattering	Detects particulate-matter concentration
Measurement range	0–1,000 µg/m ³	Defines the manufacturer-specified operating range
Communication gateway	Protoss-PG41 RS485-to-4G gateway	Receives sensor data and transmits it to the cloud
Sensor–gateway interface	RS485 Modbus RTU	Transfers measurements from the monitoring unit to the gateway
Outdoor network	4G cellular network	Transfers data from the outdoor station to the cloud server
Application protocol	MQTT	Publishes monitoring data to the cloud system
Solar panel	100 W monocrystalline panel	Supplies electrical power to the station
Backup batteries	Two 12 V, 20 Ah batteries	Support operation during limited sunlight
Comparison monitor	IQAir AirVisual	Provides simultaneous measurements for comparison

The AQMS was not compared with a Federal Reference Method (FRM) or Federal Equivalent Method (FEM) certified instrument, and no correction equation was developed. Instead, its measurements were compared with those from an IQAir AirVisual commercial monitor.

The AQMS and IQAir AirVisual were installed in the same general area, with their air inlets approximately 4 meters apart and at a height of about 2.5 meters above ground level. Both devices recorded measurements during the same 30-day period. AQMS data recorded at 60-second intervals were processed and converted into hourly averages. After alignment, 720 paired hourly observations were obtained.

Measurement agreement was evaluated using MAPE, MAE, and RMSE. These metrics represent the differences between the two devices under the study conditions and do not confirm the absolute accuracy of the AQMS because IQAir AirVisual is not an FRM/FEM comparison monitor.

2.2.4 Design of the data display system

After the data were transmitted to the central system, display interfaces were designed for local and online monitoring. The LED display at the station showed current PM_{2.5} levels, color-coded according to the air quality index and accompanied by warning messages, enabling immediate recognition. The web dashboard provided an overview of all stations by showing their locations on a map and graphing and summarizing real-time PM_{2.5} values to support clear trend analysis.

2.2.5 Design of the alert system via application

The researchers developed an automated Telegram notification system to promptly communicate air quality risks based on readings from selected monitoring stations. To simplify automated notifications, the five AQI categories were consolidated into three alert groups: good (Very Good, Good, and Moderate: ≤ 37.5 µg/m³), poor (Beginning to Affect Health: 37.6–75.0 µg/m³), and very poor (Affects Health:

$\geq 75.1 \mu\text{g}/\text{m}^3$). This helped users easily assess severity and take protective action, such as limiting outdoor activities or using protective equipment. Automated alerts were sent to members of the Telegram group when the predefined PM2.5 threshold conditions were met.

2.2.6 Prototype development

After designing the system components, the researchers developed a prototype that functioned as an integrated whole, encompassing air quality data measurement, network data transmission, server storage and processing, web dashboard display, and application-based alerts. Development focused on three main areas: the air quality monitoring station, the web dashboard display, and Telegram notifications. The diagram illustrates the devices within the air quality station and the display, as shown in Figure 2. The results demonstrated that all components were correctly connected and operated continuously.

In summary, the system analysis, design, and development stage was an important process that enabled the researchers to transform knowledge from the literature review into a usable prototype system. It covered hardware, software, data communication, display, and notification dimensions, resulting in a system with the potential for concrete use in local air quality surveillance and environmental risk communication.

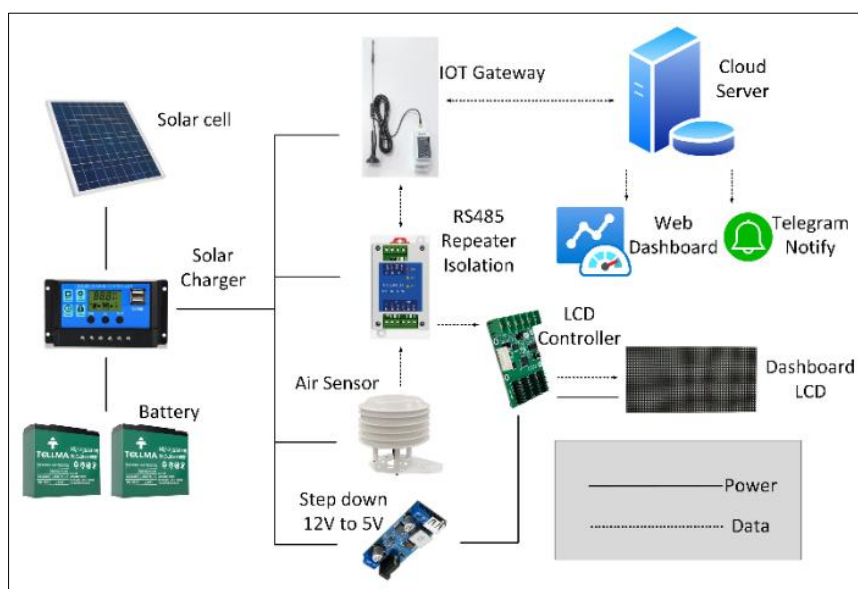


Figure 2. Diagram of devices inside the air quality monitoring station and display

2.3 System functional and measurement agreement evaluation

The evaluation consisted of two components: functional verification of the predefined system operations and evaluation of measurement agreement between the AQMS and the IQAir AirVisual commercial monitor. Functional verification examined whether the system produced the expected observable outputs for monitoring, data transmission, processing, display, classification, and notification. The evaluation did not include a comprehensive quantitative assessment of network or system performance, such as latency, packet loss, system uptime, response time, or notification delay.

2.3.1 Functional verification using Black-Box testing

Black-box testing (Sommerville, 2021) was used to verify that predefined system functions produced the desired visible outputs without examining the internal program structure. The

verification covered PM2.5 and temperature data acquisition, RS485 communication between the monitoring unit and the gateway, 4G data transmission to the cloud server, server-side data processing and storage, web dashboard display, LED display, air-quality classification, and Telegram notifications.

The verification was performed in two stages. The alpha test was conducted in a controlled environment to assess the performance of the respective system functions, including data acquisition, communication, processing, display, classification, and notification. During the study period, the integrated workflow of the system under development was validated outdoors. The black-box testing was limited to functional verification and did not include any quantitative evaluation of latency, packet loss, system uptime, response time, notification delay, or long-term operational reliability.

2.3.2 Evaluation of Measurement Agreement Using Error Metrics

The AQMS recorded PM2.5 measurements at 60-second intervals. Measurements recorded within each clock hour were grouped, and the arithmetic mean of the available observations was calculated to produce one hourly mean value. An hourly mean was retained only when at least 45 of the expected 60 minute-level measurements were available. This hourly averaging reduced short-term fluctuations and random variability in the minute-level measurements; however, no separate moving-average filter or outlier-removal procedure was applied. The hourly AQMS measurements were then time-aligned with the corresponding hourly measurements obtained from a nearby IQAir AirVisual commercial monitor. Only hours with valid measurements from both devices were included in the paired analysis, resulting in 720 paired hourly observations collected over 30 consecutive days. The AirVisual device is certified by IQAir (IQAir, 2026). Measurement agreement between the AQMS and the IQAir AirVisual commercial monitor was quantified using the Mean Absolute Percentage Error (MAPE), Mean Absolute Error (MAE), and Root Mean Squared Error (RMSE), as shown in Equations (1), (2), and (3).

$$MAPE = \frac{100}{n} \sum_{i=1}^n \left| \frac{y_i - \hat{y}_i}{y_i} \right| \quad (1)$$

$$MAE = \frac{1}{n} \sum_{i=1}^n |y_i - \hat{y}_i| \quad (2)$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2} \quad (3)$$

where y_i = value measured by IQAir AirVisual at the i^{th} data point
 $\hat{y}_i$ = value measured by the AQMS at the i^{th} data point
 n = total number of data points

The performance evaluation in this study verified the system's functionality and quantified differences between the two devices in the measured data. These results demonstrate the system's potential for practical application in local air quality surveillance.

2.4 Pilot User Acceptance Evaluation

The researchers conducted a pilot user acceptance evaluation to assess perceptions and adoption of the real-time air quality monitoring and PM2.5 alert system. This evaluation was used to examine the system's suitability for practical use, including responsiveness to user needs, system design, performance, and usability. Lecturers, staff, students, and members of the public participated in the evaluation.

2.4.1 Evaluation Sample Group

The pilot acceptance evaluation included four types of users, namely, lecturers, staff, students, and the public, to reflect the diversity of users within the framework of the study. The population was divided into four user types, and purposive sampling (Oguguo et al., 2026) was applied to each group to ensure representation of all user types in the evaluation, yielding a final sample of 30 participants.

2.4.2 The acceptance evaluation tools

The acceptance evaluation tool was a 20-item questionnaire covering four dimensions: functional requirements, design, functionality, and usability. The questionnaire used a Likert scale (Likert, 1961). The content validity of the questionnaire was assessed by three experts using the Index of Item–Objective Congruence (IOC). The IOC values ranged from 0.67 to 1.00, exceeding the acceptability criterion of 0.50. The items were subsequently revised for clarity before data collection. However, internal consistency reliability was not examined in this pilot study. Therefore, the questionnaire results should be interpreted as descriptive feedback.

2.4.3 Data Analysis

The researchers used descriptive statistics to analyze the questionnaire results and assess user acceptance of the developed system. The analysis included the mean and standard deviation. Mean scores were interpreted using a five-level Likert scale: scores of 4.50 to 5.00 indicated the highest acceptance; scores of 3.50 to 4.49 indicated high acceptance; scores of 2.50 to 3.49 indicated moderate acceptance; scores of 1.50 to 2.49 indicated low acceptance; and scores of 1.00 to 1.49 indicated the lowest acceptance. This framework provided a systematic basis for explaining user acceptance.

3. Results

The development of a real-time air quality monitoring and PM2.5 alert system using Internet of Things technology showed that the system met its specified objectives. These objectives included air quality data monitoring, data transmission from monitoring stations to the central system, data processing and display on the web dashboard, and real-time notifications to users via the application. To present the findings clearly, the results were divided into three parts: 1) system development results, 2) performance evaluation results, and 3) pilot user acceptance evaluation results.

3.1 System Development Results

The results showed that the real-time air quality monitoring and PM2.5 alert system based on Internet of Things (IoT) technology achieved the research objective. The system architecture consisted of PM2.5 monitoring stations that collected outdoor data and transmitted them via a 4G network using the MQTT protocol to a cloud server for processing, storage, and forwarding to a web dashboard and user alert service, as illustrated in Figure 3. The system continuously monitored, tracked, transmitted, and processed air quality data. It was divided into three main parts: (1) air quality monitoring stations, as shown in Figure 4; (2) a web dashboard display system, as shown in Figure 5; and (3) an alert system using Telegram notifications, as shown in Figure 6. These three parts were integrated into one system.

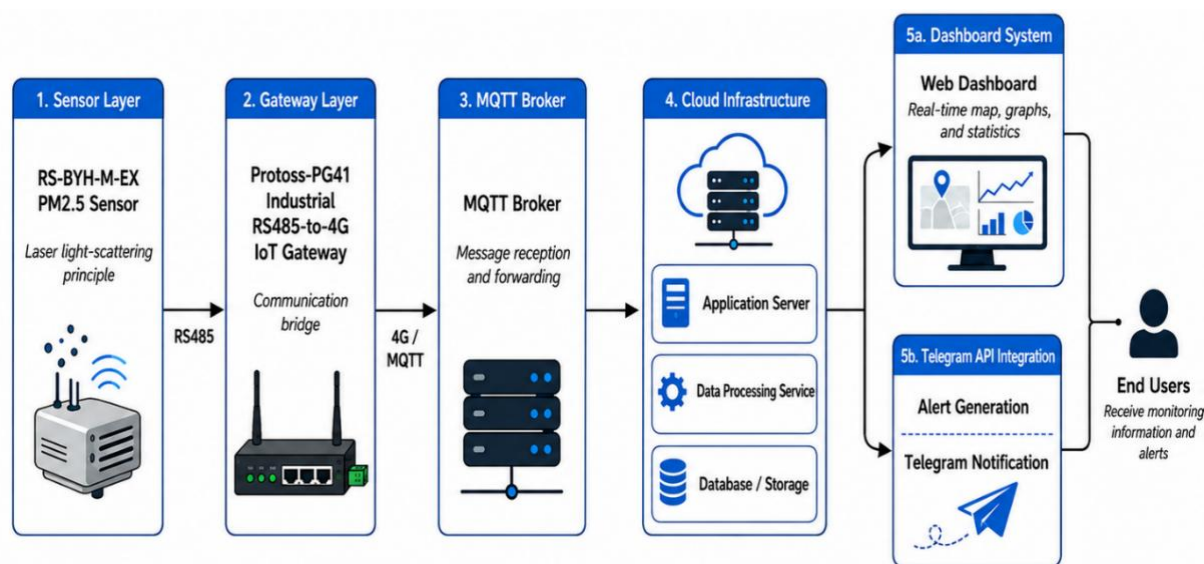


Figure 3. System Architecture



Figure 4. Air Quality Monitoring Station

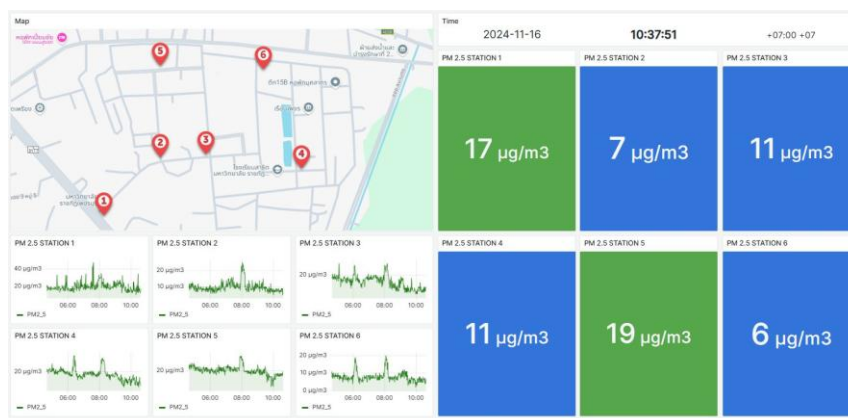


Figure 5. Web dashboard display screen

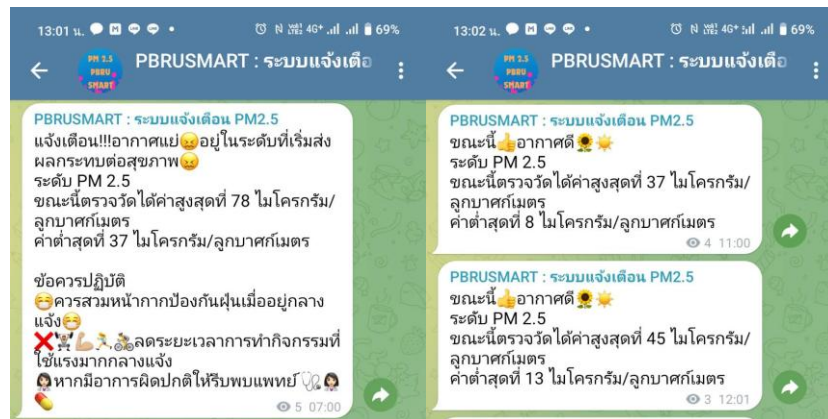


Figure 6. PM2.5 notification via Telegram notifications

In summary, the developed system included monitoring, processing, display, and notification functions, demonstrating the potential of Internet of Things technology to support local air pollution surveillance, as shown in Table 3.

Table 3. Summary of System Development Results

System Component	Development Details	Result
Air quality monitoring station	Developed an outdoor monitoring station with PM2.5 and temperature sensors, powered by a solar energy system and backup batteries	Able to continuously monitor and transmit data in a real-world environment
Data transmission system	Used an IoT gateway to transmit data over a 4G network to the central server	Enabled rapid, continuous data transmission to the central system
Web dashboard	Displayed real-time PM2.5 data as maps, graphs, and statistics	Users could easily monitor the air quality
LED display screen	Displayed PM2.5 values and warning messages at the station installation site	Helped directly communicate information within the installation area
Telegram notifications alert system	Automatically alerted at three levels based on air quality criteria	Users could recognize risks and protect themselves in time

3.2 System Functional and Measurement Agreement Evaluation Results

3.2.1 Functional Verification Results Using Black-Box Testing

Black-box testing was conducted to verify whether the developed system completed the predefined functional operations. The verification covered data acquisition, RS485 communication, 4G data transmission, server-side processing and storage, web dashboard display, LED display, air-quality classification, Telegram notification, and integrated system operation. The observed outputs were compared with the predefined expected results for each test item. All ten functional test items produced the expected observable outputs and were therefore classified as Pass. These findings represent functional verification only and should not be interpreted as a comprehensive assessment of network performance, long-term stability, or operational reliability. Details are shown in Table 4.

3.2.2 Evaluation of Measurement Agreement Using Error Metrics

The comparison of 720 paired hourly PM_{2.5} measurements collected over 30 days yielded an MAPE of 7.72%, an MAE of 1.65 $\mu\text{g}/\text{m}^3$, and an RMSE of 1.96 $\mu\text{g}/\text{m}^3$. These results indicate that the AQMS measurements differed from the IQAir AirVisual measurements by approximately 1.96 $\mu\text{g}/\text{m}^3$ under the specific location, period, and environmental conditions of the study, suggesting close agreement between the two devices within the evaluated dataset.

However, the findings should not be interpreted as evidence of absolute measurement accuracy because IQAir AirVisual is a commercial optical monitor rather than an FRM/FEM comparison monitor, as shown in Figure 7.

Table 4. Functional Verification Results Using Black-Box Testing

Functional Test	Predefined Expected Behavior	Observed Result	Status
PM _{2.5} data acquisition	The system receives a PM _{2.5} value from the monitoring unit	PM _{2.5} values were received and stored	Pass
Temperature data acquisition	The system receives a temperature value	Temperature values were received and stored	Pass
Sensor-to-gateway communication	The gateway receives data through RS485 Modbus RTU	Sensor data were received by the gateway	Pass
4G data transmission	The gateway delivers monitoring data to the cloud server	Data were delivered to the server during the test	Pass
Server processing and storage	The server processes and stores received data	Received data were processed and stored	Pass
Web dashboard display	The dashboard displays the received values	PM _{2.5} values were displayed on the dashboard	Pass
LED display	The LED unit displays the current PM _{2.5} level	The received PM _{2.5} value and warning level were displayed	Pass
Threshold notification	An alert is generated when the predefined threshold is met	Telegram notifications were generated under the tested threshold conditions	Pass
Air-quality classification	The system classifies values according to predefined rules	Test values were assigned to the expected categories	Pass
Integrated operation	Monitoring, transmission, storage, display, and notification operate sequentially	The predefined workflow was completed during the test	Pass

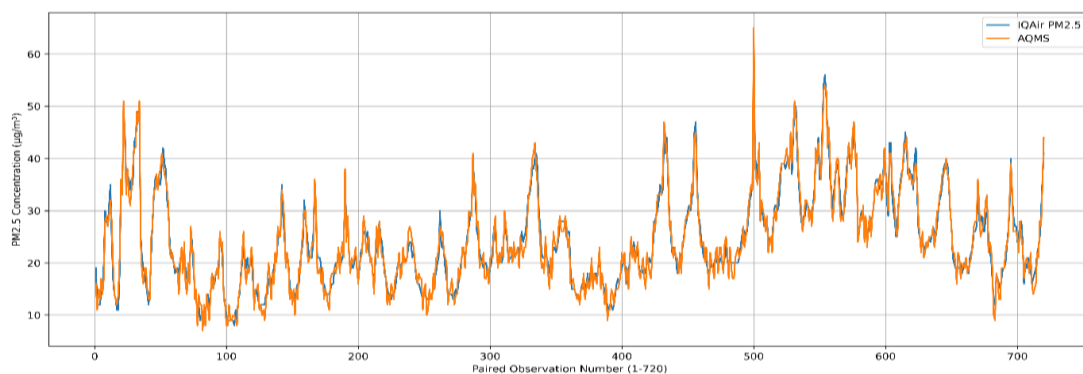


Figure 7. Comparison of 720 time-aligned paired hourly PM_{2.5} observations obtained from the AQMS and IQAir AirVisual over 30 days.

3.3 Pilot User Acceptance Evaluation Results

The pilot user acceptance evaluation of the real-time air quality monitoring and PM_{2.5} alert system was conducted using a questionnaire distributed to a sample group comprising lecturers, staff, students, and members of the public. The mean and standard deviation were used to analyze the data and evaluate user acceptance of different system features.

The results showed that users accepted the system at the highest level, with a mean of 4.51 and a standard deviation of 0.51. When each aspect was considered, functionality had the highest mean of 4.60, corresponding to the highest level, followed by usability, with a mean of 4.50 at the highest level; functional requirements, with a mean of 4.48 at a high level; and design, with a mean of 4.47 at a high level, as shown in Table 5.

Table 5. Pilot User Acceptance Evaluation Results (n = 30)

Evaluation Item	$\bar{x}$	<i>S.D.</i>	Acceptance Level
1. Functional Requirements	4.48	0.50	High
2. Design	4.47	0.50	High
3. Functionality	4.60	0.52	Highest
4. Usability	4.50	0.50	Highest
Overall Average	4.51	0.51	Highest

4. Discussion

This research developed a real-time air quality monitoring and alert system that builds on previous work by improving system architecture, data communication stability, measurement agreement, and alert channels. The results demonstrate the system's suitability for real-world applications.

Regarding infrastructure and connectivity, Phonrit et al. (2020) and Pongphab and Santakij (2021) used Wi-Fi networks for data transmission. In the present study, a 4G cellular network was selected because fixed Wi-Fi infrastructure was not consistently available at the outdoor installation site. The 4G connection was combined with the MQTT protocol to transmit monitoring data from the outdoor station to the cloud server. This design should be interpreted as a context-specific solution for the study site rather than evidence that 4G is generally superior to Wi-Fi, as no direct comparison between the two network technologies was conducted.

The present study extended previous work by quantitatively evaluating measurement agreement using 720 paired hourly observations. This study reported PM_{2.5} measurement results with an RMSE of 1.96 µg/m³, based on a comparison dataset of 720 hourly averages. This indicates a low level of measurement difference and provides quantitative evidence of agreement when compared with the research of Pongphab and Santakij (2021), which used 100 test datasets, and the research of Tantatsanawong (2026), which did not report quantitative error from direct sensor measurements because it used air quality data from the OpenWeather API, an external data source not derived from measurements taken in the actual experimental area.

This research integrated several communication channels, including Telegram notifications, a web dashboard, and an LED display, to provide public access to information. The system supports both individual users and people in public spaces. This differs from the study by Pongphab and Santakij (2021), which focused on LINE notifications, and the study by Tantatsanawong (2026), which developed a specific

smartphone application. Both approaches may have limitations related to application installation and users' internet connectivity.

Regarding user acceptance, this research achieved an overall average acceptance score of 4.51, corresponding to the highest level. This score exceeds the average score of 4.10 reported by Pongphab and Santakij (2021) and is close to the evaluation results of Tantatsanawong (2026), who reported average scores ranging from 4.30 to 4.70. Furthermore, the standard deviation in this research was low (S.D. = 0.51), indicating that user opinions of the system were consistent within the study sample.

Although the developed real-time PM_{2.5} monitoring and alert system demonstrated strong measurement agreement, functional reliability, and user acceptance, several limitations remain. Outdoor measurements may be affected by dust accumulation, weather changes, physical obstructions, airflow variation, and the 4-meter spacing between devices. Moreover, the RMSE reflects agreement with IQAir AirVisual under the study conditions rather than absolute accuracy because no FRM/FEM comparison or environmental correction model was applied.

Network instability may occasionally delay or interrupt data transmission. Cybersecurity was also not formally assessed through penetration testing, vulnerability scanning, or attack simulation; therefore, the security of the MQTT broker, gateway, cloud system, web dashboard, and API credentials, as well as resistance to unauthorized access or denial-of-service attacks, requires further evaluation.

The black-box testing verified the observable functions of the developed system under the tested conditions. However, because latency, packet loss, system uptime, response time, and notification delay were not quantitatively recorded, the results should not be interpreted as a comprehensive evaluation of system or network performance.

The user acceptance assessment was limited by the small pilot sample and the absence of a formal technology acceptance framework. Future studies should conduct co-location comparisons with standard instruments, develop independent comparison and validation datasets, test the system across different seasons and pollution conditions, implement automated logging, evaluate cybersecurity, and apply a validated Technology Acceptance Model (TAM)-based instrument to a larger and more diverse sample. In addition, the questionnaire's internal consistency reliability was not examined. Therefore, the user evaluation findings should be interpreted as descriptive and specific to the participants in this study and should not be generalized to the broader user population.

Furthermore, this research provides avenues for future development. It is recommended that the scope of measurements be expanded to include additional air quality parameters, such as PM₁₀, humidity, and carbon dioxide, and that machine learning techniques be applied to forecast air quality trends. This aligns with the recommendations of the related research mentioned above and would upgrade the system from real-time monitoring and alerts to a more efficient air quality monitoring and decision-support system.

5. Conclusions and Recommendations

The developed system integrated an outdoor PM_{2.5} monitoring station, RS485 communication, a 4G cellular gateway, MQTT-based cloud transmission, a web dashboard, an on-site LED display, and automated Telegram notifications. During the study period, all ten black-box testing items produced the expected observable outputs for monitoring, transmission, processing, display, classification, and notification. These results represent functional verification under the tested conditions and do not constitute a comprehensive assessment of network performance, long-term stability, or operational reliability.

The comparison of 720 paired hourly observations collected over 30 days yielded an MAPE of 7.72%, an MAE of 1.65 $\mu\text{g}/\text{m}^3$, and an RMSE of 1.96 $\mu\text{g}/\text{m}^3$, indicating close measurement agreement between the AQMS and the IQAir AirVisual commercial monitor under the study conditions. However, the findings do not establish absolute measurement accuracy because the AQMS was not calibrated against a regulatory-grade FRM/FEM instrument, and no environmental correction model was developed.

The pilot user acceptance evaluation of 30 participants yielded an overall mean score of 4.51 and a standard deviation of 0.51. These results reflect descriptive feedback from the participants and should not be generalized to the broader population because the sample was limited and the questionnaire's internal consistency was not examined.

Before wider deployment, future studies should include calibration and validation with a regulatory-grade instrument; long-term testing across multiple locations and seasons; quantitative evaluation of latency, packet loss, uptime, response time, and notification delay; and a formal cybersecurity assessment. Larger user samples and validated usability or technology acceptance instruments should also be used. Additional air quality parameters and machine-learning methods may be incorporated to support forecasting and decision-making.

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