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IoT Based Air Quality Monitoring System Using LoRaWAN

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Abstract

Insufficient local air quality data hinders control efforts, exacerbating public health and economic concerns amid rising deforestation and urbanization. This project implements an IoT-based air quality monitoring system to track outdoor gas and dust concentrations, fostering public awareness of current pollution levels. The system incorporates an array of sensors, including DHT11, MQ9, MQ135, and a dust sensor, to quantify temperature, humidity, carbon monoxide, carbon dioxide, and PM2.5 levels. A LoRa-enabled microcontroller used to transmit sensor data via a gateway to The Things Network (TTN) platform. TTN seamlessly integrates with ThingSpeak, an IoT server, making the collected environmental data publicly accessible through a web-based ThingSpeak channel and a mobile GUI within the Virtuino application. This design enables users to access real-time data conveniently via a mobile application. The system employs the Malaysian Department of Environment's Air Quality Index (AQI) to categorize pollution severity (good to hazardous). Sensor data from the Air Quality Monitoring system is validated against readings from a Temtop air quality monitoring device, confirming its reliability in measuring CO, CO2, and PM2.5 concentrations.

1. Introduction

As human activities like deforestation and urbanization intensify, air pollution becomes a pressing issue requiring immediate attention in the 21st century. The rapid rise of large factories globally, while driving economic growth, has a hidden cost: air pollution. These facilities emit harmful and toxic gases, posing significant health risks. Human activities, including industrial processes and vehicle emissions, contribute further by releasing pollutants like particulate matter, hazardous substances, and biological molecules [1], [2]. These pollutants lead to a cascade of environmental problems. Emissions like carbon dioxide (CO2), sulfur dioxide (SO2), carbon monoxide (CO), PM2.5, and nitrogen dioxide (NO2) worsen air quality, contributing to global warming, acid rain, and a range of health issues [3], [4].

The rise of the Internet of Things (IoT) signifies a fundamental change in device connectivity. This shift prioritizes widespread accessibility and embedded intelligence within devices. This interconnected ecosystem, enabled by diverse communication technologies, has empowered a new era of environmental monitoring through sensor networks [5]. IoT paves the way for a symphony of connected devices, fostering seamless communication and user integration with the internet. This vast data collection fuels advancements in applications like smart cities, homes, environmental monitoring, and healthcare. Notably, IoT transforms user interactions by providing high-performance networking and socially enriched interfaces.

In this work, an IoT-based air quality monitoring system will be developed and deployed in Parit Raja Industrial Park, Hotel Pintar, Taman Universiti, and Kg Parit Hj Salleh Ros. The system utilizes LoRa technology to transmit sensor data on pollutant concentrations to cloud server via a LoRaWAN gateway. This work aims to quantify pollutant concentrations in designated areas and provide real-time data to the public, raising awareness of local air quality conditions. The system employs sensors to measure temperature, humidity, carbon monoxide, carbon dioxide, and Particulate Matter 2.5. The collected data is then transmitted to The Thing Network and displayed on ThingSpeak and the Virtuino Mobile application for remote user access. The mobile application features an alert system that notifies users when pollutant concentrations exceed predefined thresholds, keeping them informed about air quality.

2. Methodology

Fig. 1 illustrates the block diagram of the system, highlighting input and output elements. The Arduino Uno and LoRa shield serve as the primary control unit. A photovoltaic solar cell connected to rechargeable Lithium-Ion battery to recharge the battery and powers the system subsequently. Upon activation, sensors detect specific pollutants: dust sensor measures PM2.5 concentration, while the DHT11 measures temperature and humidity. MQ9 and MQ135 sensors quantify CO and CO2 concentrations. Sensor data transmits to the LoRa node, which relays it to the gateway. The LoRaWAN gateway then uploads data payloads to The Thing Network (TTN) server. LoRaWAN technology is employed instead of Wi-Fi due to insufficient Wi-Fi coverage in the deployment areas and enables to establish long-range communication between LoRaWAN gateways and LoRa node. The server seamlessly integrates with ThingSpeak and the Virtuino mobile app. Users can access real-time air quality data through a web-based dashboard or a mobile GUI, enabling convenient remote monitoring.

The flowchart in Fig. 2 explains the flow of the system. The process begins with powering on the sensors for pollutant measurement. Measured parameters transmit wirelessly from Arduino Uno to the gateway via the LoRa Shield for upload to The Thing Network (TTN) cloud server. ThingSpeak facilitates data analysis by presenting it graphically. The Virtuino app employs a custom GUI to display data to users and generates alerts with notifications when CO, CO2, or PM2.5 concentrations exceed healthy levels.

Table 1 presents the Air Quality Index (AQI), a numerical rating system (0-500) established by the USEPA to categorize air quality. Higher AQI values correspond to poorer air quality. An AQI exceeding 300 signifies hazardous conditions, while values below 50 represent good air quality [6]. Following the collection of data for each pollutant parameter, Eq. (1) can be employed to calculate the AQI for each pollutant. This equation, derived from the US Environmental Protection Agency's (USEPA) Air Quality Index (AQI) framework, determines the corresponding air quality category for the monitored area.

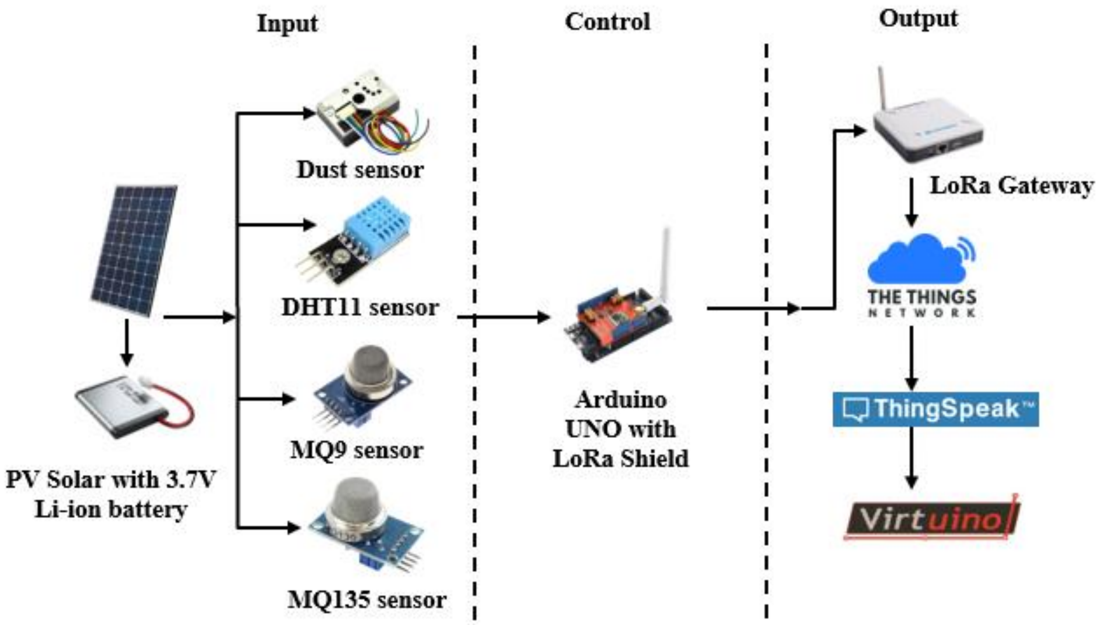


Fig. 1 *Block diagram of IoT-Based Air Quality Monitoring System using LoRaWAN*

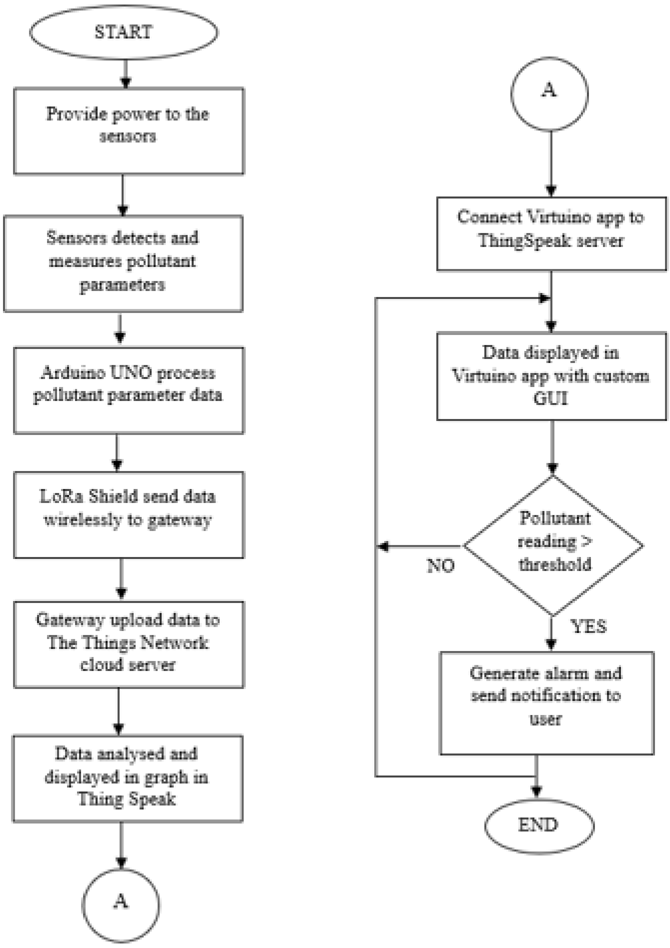


Fig. 2 *Flowchart of the system*

Table 1 *Breakpoints values for the API calculation based on USEPA [7]*

Category Parameter Averaging Time	AQI	Parameter Breakpoint PM2.5 (µg/m3) 24-h	 CO (ppm) 8-h	 SO2 (ppm) 1-h	 NO2 (ppm) 1-h
Good	0 – 50	0.0-12.0	0.0-4.4	0.000-0.035	0.000-0.053
Moderate	51 - 100	12.1-35.4	4.5-9.4	0.036-0.075	0.054-0.100
Unhealthy For Sensitive Groups	101 - 150	35.5-55.4	9.5-12.4	0.076-0.185	0.101-0.360
Unhealthy	151 – 200	55.5-150.4	12.5-15.4	0.186-0.304	0.361-0.649
Very Unhealthy	201 – 300	150.5-250.4	15.5-30.4	0.305-0.604	0.650-1.249
Hazardous	301 – 400	250.5-350.4	30.5-40.4	0.605-0.804	1.250-1.649
Hazardous	401 - 500	350.5-500.4	40.5-50.4	0.805-1.004	1.650-2.049

Table 2 *Breakpoints values for Carbon Dioxide based on EPA standard [8]*

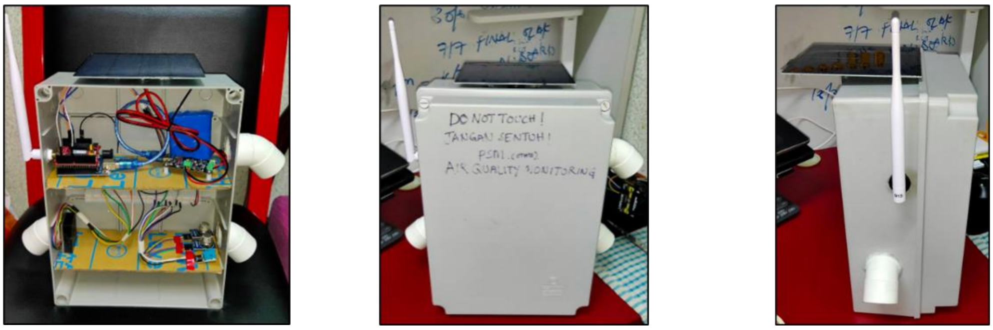
Category	Parameter Breakpoint
Good	≤ 700
Moderate	701 - 1000
Unhealthy For Sensitive Group	1001 - 1500
Unhealthy	1501 - 2500
Very Unhealthy	2501 - 5000
Hazardous	≥ 5001

$$I_p = \frac{I_{Hi} - I_{Lo}}{BP_{Hi} - BP_{Lo}}(X_p - BP_{Lo}) + I_{Lo} \quad (1)$$

3. Result and Discussion

3.1 Hardware Prototype

The Arduino Uno serves as the project's core processing unit. The Dragino LoRa Shield, attached to the Arduino Uno, facilitates wireless communication between the sensor node and the gateway for data transmission. Various sensors, including DHT11, MQ9, MQ135, and a dust sensor, connect to the Arduino board via designated pins. The DHT11 sensor connects to digital pin 2, while MQ9, MQ135, and the dust sensor connect to analog pins A0, A1, and A2, respectively. To enable continuous operation, a rechargeable battery and solar cell are integrated with the system using a solar power manager compatible with the Arduino board. This allows the battery to recharge through solar energy. The Arduino Uno draws power when connected via USB cable to the power output port of the solar power manager. Finally, a PVC junction box serves as the enclosure for all electronic components, ensuring the prototype's suitability for outdoor deployment.

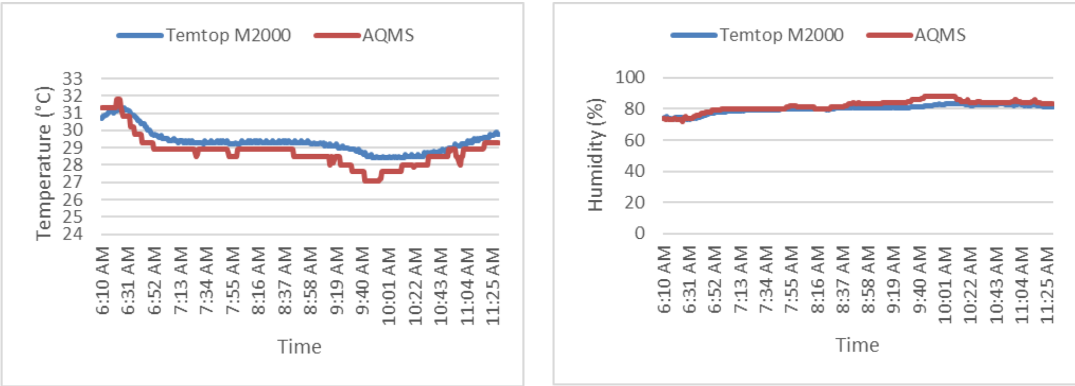


(a) (b) (c)

Fig. 3 *(a) Interior view; (b) Exterior view; (c) Side view*

3.3 Validation of result

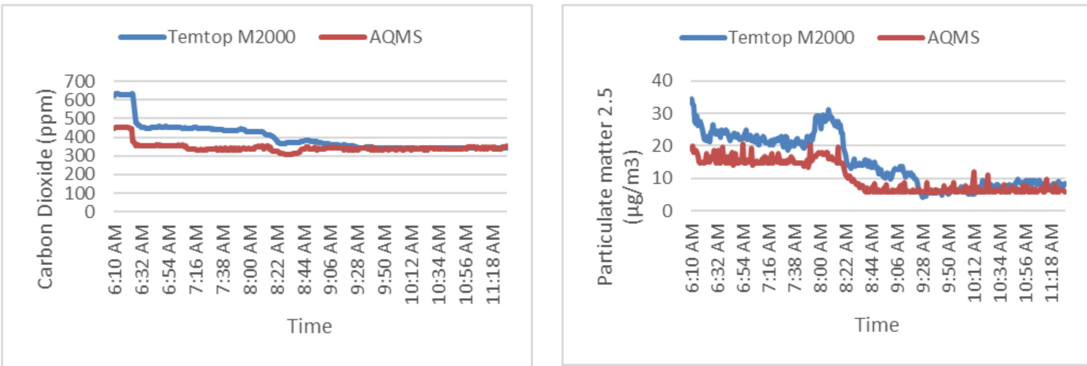
Data validation serves as an initial screening step preceding data analysis. Data collected during the designated testing period undergoes comparison with real-world measurements obtained from a commercially available, high-accuracy handheld air quality device, the Temtop M2000. Affordability and measurement accuracy [9] were the primary considerations for selecting this device.



(a) **(b)**

Fig. 4 *(a) Comparison of Temperature reading; (b) Comparison of Humidity reading*

The Temtop M2000 handheld air quality monitor was positioned near the Air Quality Monitoring System (AQMS) for data comparison. Data logged by the Temtop device was transferred via USB cable to a laptop. Given the proximity of the AQMS and Temtop device, minimal variations in pollutant concentrations were anticipated. However, analysis revealed discrepancies in the results, potentially attributable to wind direction and speed, as these factors influence airborne pollutant dispersion. Temperature data was evaluated first. Fig. 4(a) and (b) present comparative results from both systems. Temperature readings exhibited slight deviations (±1.5 °C) between the AQMS and Temtop device. However, the overall trends in the graphs were nearly identical. This analysis validates the performance of the DHT11 temperature sensor within the AQMS for monitoring ambient air temperature. The same sensor was employed for humidity monitoring. Sensor readings displayed minor variations (±5.5%). Consistent graphical trends suggest the sensor's suitability for real-time ambient air humidity data collection within the system.



(a) **(b)**

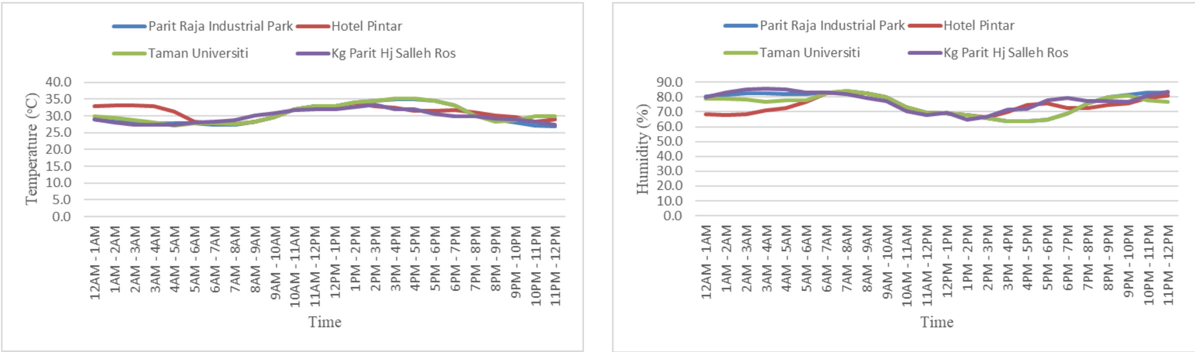
Fig. 5 *(a) Comparison of Carbon Dioxide; (b) Comparison of PM2.5 reading*

Fig. 5 (a) and (b) depict comparative results for CO2 and PM2.5, respectively. Initial CO2 readings displayed some divergence, but the curves converged within a few hours, suggesting a similar trend with diminishing discrepancies. Likewise, PM2.5 data from the AQMS dust sensor exhibited a difference of approximately ±6 µg/m3 compared to the Temtop device. Notably, both graphs maintained consistent trends over time.

3.4 Result analysis

3.4.1 Result comparison for different areas

This section presents a comparison of results recorded on the following dates: May 16, 2024 (Parit Raja Industrial Park), May 22, 2024 (Hotel Pintar), June 7, 2024 (Taman Universiti), and May 27, 2024 (Kg Parit Hj Salleh). Fig. 6(a) and (b) depict the hourly average values for recorded temperature and humidity data, respectively. Figure 6(a) reveals slight temperature variations across different areas, potentially attributable to weather phenomena such as rain. Notably, the Hotel Pintar area recorded the highest average temperature of 33°C between 12 AM and 1 AM, possibly due to the release of heat accumulated during earlier high-activity periods [10]. Conversely, Figure 6(b) shows a lower average humidity value in the Hotel Pintar area during the same time frame, likely a consequence of the temperature increase.

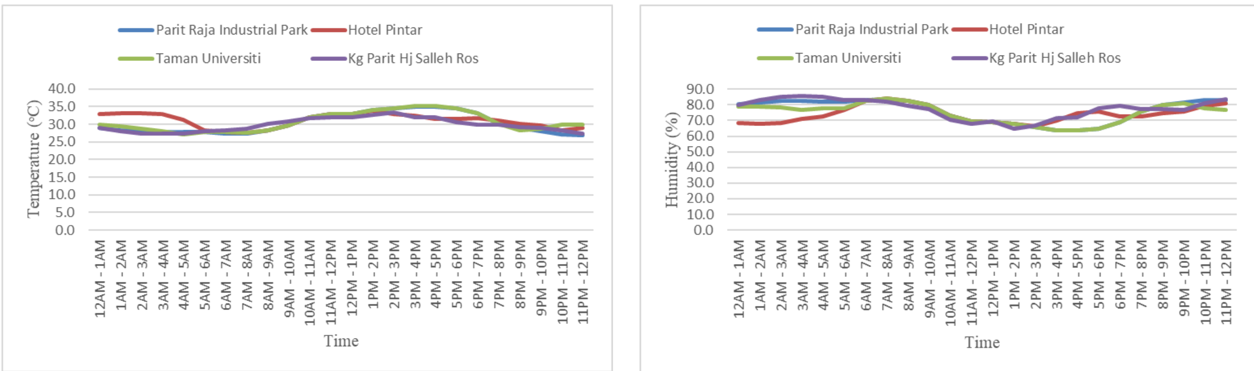


(a) **(b)**

Fig. 6 *(a) Average temperature; (b) Average humidity*

Fig. 7(a) and (b) depict the hourly average concentrations of Carbon Monoxide (CO) and Carbon Dioxide (CO2), respectively. Fig. 7(a) shows variations in CO concentration across the areas. The highest average (16.4 ppm) occurred in the Hotel Pintar area between 1 PM and 2 PM. This increase likely stems from elevated traffic volume and associated emissions from automobiles and commercial vehicles. Parit Raja Industrial Park area exhibited a slightly lower peak (15.5 ppm) at 2 PM to 3 PM, likely due to moderate traffic consisting primarily of industrial transport vehicles. Industrial activity in this area also contributes to CO emissions. Notably, both areas exceed the USEPA's healthy air quality standards for CO. Taman Universiti and Kg Parit Hj Salleh Ros recorded lower average CO concentrations (6.10 ppm and 3.4 ppm, respectively). The distance from industrial zones and moderate traffic contribute to moderate CO level in Taman Universiti. Kg Parit Hj Salleh Ros's minimal traffic activity translates to the lowest CO concentration among the monitored areas.

Fig. 7(b) illustrates the average CO2 concentrations across areas. Parit Raja Industrial Park and Hotel Pintar recorded the highest average CO2 levels (664.9 ppm and 699.3 ppm, respectively) between 12 PM and 1 PM. These elevated readings likely result from heavy traffic activity and industrial emissions in both areas. While the Temtop Air Quality Monitor Data Sheet classifies these levels as good and moderate [8], it's important to consider the typical outdoor CO2 range of 300-400 ppm [11]. In metropolitan areas, this range can extend to 600-900 ppm. Taman Universiti and Kg Parit Hj Salleh Ros exhibited good average CO2 values, with peak recordings of 571.4 ppm (Taman Universiti, 8 AM to 9 AM) and 474.7 ppm (Kg Parit Hj Salleh Ros, 3 PM to 4 PM). This is likely due to lower exposure to heavy traffic and industrial emissions in these areas.



(a) **(b)**

Fig. 7 *(a) Average Carbon Monoxide; (b) Average Carbon Dioxide*

Fig. 8 depicts the hourly average PM2.5 concentrations across monitored areas. Hotel Pintar exhibits a gradual rise in PM2.5, starting from 36.3 µg/m3 (6 AM to 7 AM) and peaking at 46.8 µg/m3 (9 AM to 10 AM). This timeframe coincides with increased traffic volume, likely due to student and worker commutes, leading to congestion and potentially contributing to the PM2.5 surge. Parit Raja Industrial Park shows a distinct pattern. The highest average (44.00 µg/m3) occurs between 2 PM and 3 PM. However, unlike Hotel Pintar, PM2.5 concentration exhibits a steady upward trend throughout the day, starting after midnight and continuing until evening. Factors influencing this rise might include wind patterns and surrounding conditions near the recycling facility (stockpiles of wood waste and construction sand). Notably, both areas exceed the USEPA's healthy air quality standards for PM2.5, posing a risk for sensitive groups. Taman Universiti records its highest average PM2.5 (32.5 µg/m3) between 6 PM and 7 PM, potentially coinciding with increased activity around 11:25 AM, leading to higher traffic and congestion. However, PM2.5 remains within the moderate USEPA range. Kg Parit Hj Salleh Ros exhibits the lowest PM2.5 concentration (highest recorded value: 9.00 µg/m3), indicating good air quality likely due to minimal human activity and infrequent traffic. In summary, PM2.5 concentrations are high in Parit Raja Industrial Park and Hotel Pintar, moderate in Taman Universiti, and low in Kg Parit Hj Salleh Ros.

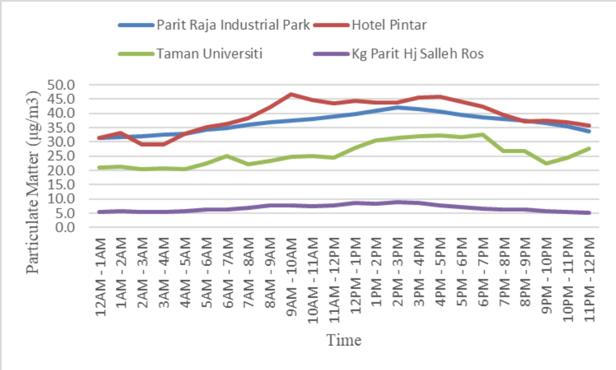


Fig. 8 *Average Particulate Matter 2.5*

3.4.2 Air Quality Index for different areas

Table 3 *AQI for PM2.5 in different areas*

Date	Parit Raja Industrial Park	Date	Hotel Pintar	Date	Taman Universiti	Date	Kg Parit Hj Salleh Ros
	AQI (Avg 24-h)		AQI (Avg 24-h)		AQI (Avg 24-h)		AQI (Avg 24-h)
12-May-24	97	19-May-24	95	7-Jun-24	80	26-May-24	26
13-May-24	104	20-May-24	98	8-Jun-24	83	27-May-24	28
14-May-24	99	21-May-24	102	9-Jun-24	80	28-May-24	29
15-May-24	104	22-May-24	110	10-Jun-24	79	29-May-24	29
16-May-24	104	23-May-24	106	11-Jun-24	79	30-May-24	27

Table 4 *AQI for Carbon Monoxide in different areas*

Date	Parit Raja Industrial Park			Date	Taman Universiti		
	AQI (Avg 8-h)				AQI (Avg 8-h)		
12-May-24	46	80	59	7-Jun-24	48	57	45
13-May-24	49	124	87	8-Jun-24	42	66	59
14-May-24	47	119	76	9-Jun-24	35	68	57
15-May-24	50	122	82	10-Jun-24	39	65	58
16-May-24	64	159	136	11-Jun-24	42	60	56
Date	Hotel Pintar			Date	Kg Parit Hj Salleh Ros		
	AQI (Avg 8-h)				AQI (Avg 8-h)		
19-May-24	46	90	70	26-May-24	18	40	36
20-May-24	50	114	91	27-May-24	29	40	31
21-May-24	43	119	76	28-May-24	28	49	36
22-May-24	90	193	141	29-May-24	28	48	49
23-May-24	42	122	76	30-May-24	28	49	36

Table 3 presents the 24-hour average PM2.5-based Air Quality Index (AQI) for five days in four areas: Parit Raja Industrial Park, Hotel Pintar, Taman Universiti, and Kg Parit Hj Salleh Ros. Parit Raja Industrial Park and

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Hotel Pintar exhibited moderate (yellow) to unhealthy for sensitive groups (orange) air quality, with AQI values ranging from 95 to 106 (Parit Raja) and 97 to 104 (Hotel Pintar). This likely stems from high traffic volume and industrial activity in both areas. Taman Universiti maintained consistently moderate air quality (yellow) throughout the period, with AQI values between 79 and 83. Kg Parit Hj Salleh Ros shows the best air quality (green), with consistently low AQI values (26-29). These variations likely reflect inherent area characteristics: moderate traffic in Taman Universiti and Kg Parit Hj Salleh Ros distance from industrial areas contribute to their better air quality.

Table 4 shows the 8-hour average CO-based Air Quality Index (AQI) for five days in four areas: Parit Raja Industrial Park, Hotel Pintar, Taman Universiti, and Kg Parit Hj Salleh Ros. Parit Raja Industrial Park exhibited variations in air quality (good to unhealthy; AQI 46-159). Lower AQI values were observed during the first eight hours (12 May - 15 May), followed by elevated CO levels indicated by higher and moderate AQI values in subsequent intervals. Hotel Pintar mirrored Parit Raja's trend (AQI 42-193) with lower values initially and higher values later. Taman Universiti maintained consistently good to moderate air quality (AQI 35-68). Kg Parit Hj Salleh Ros shows the best air quality (consistently good; AQI 18-49). These variations likely reflect CO emission levels: industrial activity likely contributes to higher emissions in Parit Raja Industrial Park, while Kg Parit Hj Salleh Ros, a residential area, exhibits lower emissions.

3.5 The Things Network Application Console

Fig. 9 depicts real-time sensor data retrieved by the gateway from LoRa Shield-equipped sensors. This data is accessible through the TTN application console and stored on the network server. Preconfigured device, channel, and network keys and IDs facilitate secure communication. Additionally, the figure displays the public ThingSpeak channel for live sensor readings. Each field in the TTN console represents a selected air parameter and updates every 30 seconds. Specifically, Field 1 corresponds to temperature (31°C), Field 2 to humidity (70%), Field 3 to CO (5.97 ppm), Field 4 to CO2 (411 ppm), and Field 5 to PM2.5 (12.69 µg/m3).

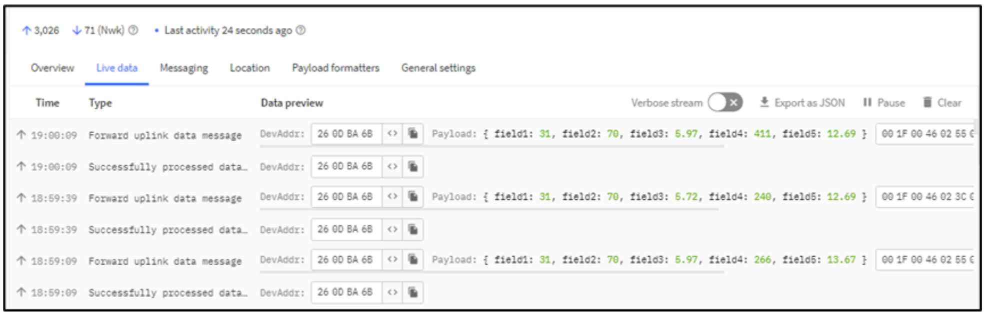
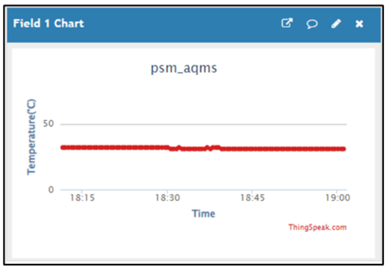
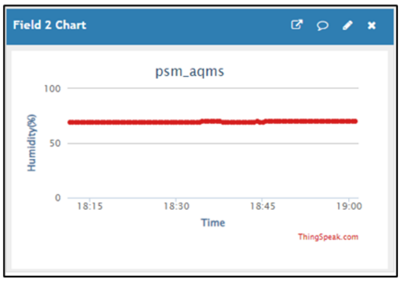


Fig. 9 *Sensor data forwarded to TTN*

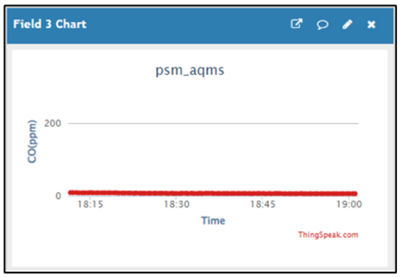
3.6 ThingSpeak Web Dashboard



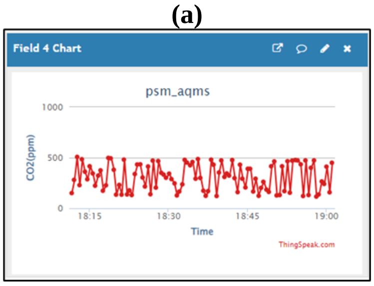
(a)



(b)



(c)



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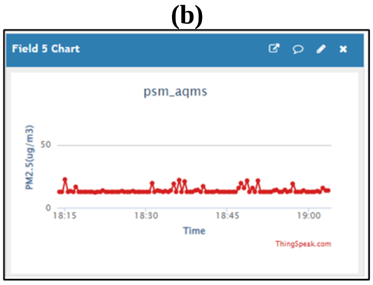
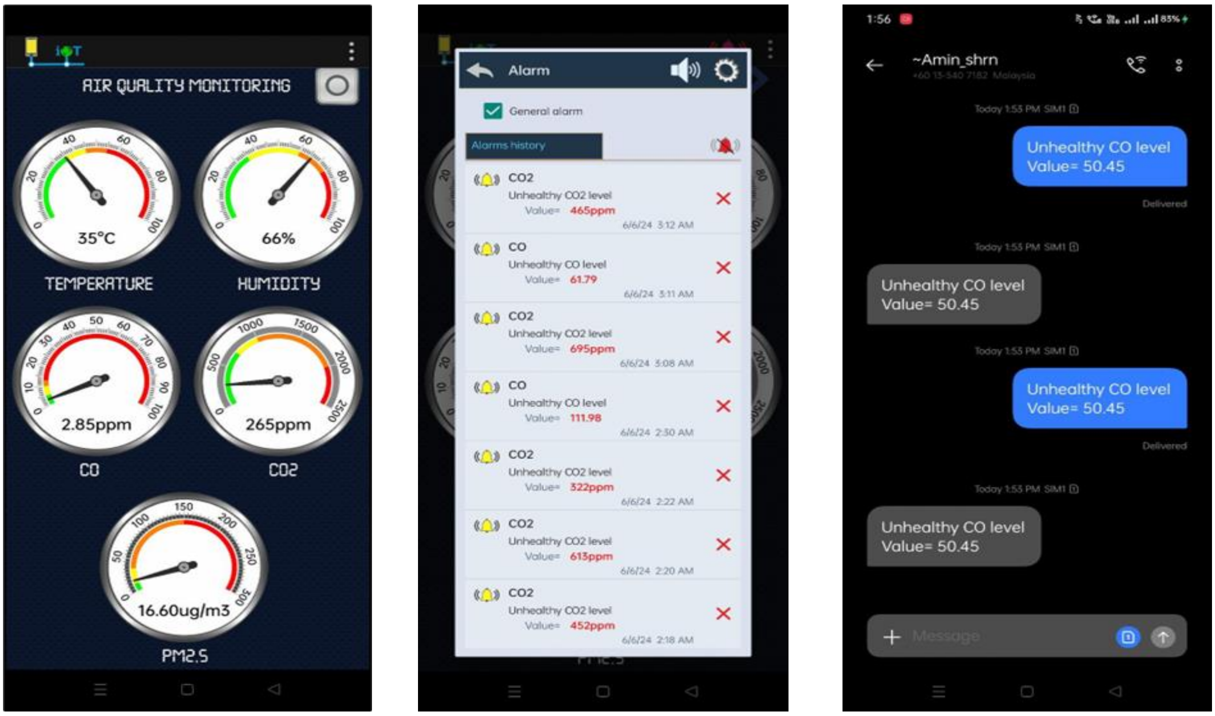


(e)

Fig. 10 *(a) Temperature field chart; (b) Humidity field chart; (c) CO field chart; (d) CO2 field chart; (e) PM2.5 field chart*

Due to security protocols on TTN utilizing private keys, limit direct public data display. Therefore, sensor data is synchronized and visualized as real-time ThingSpeak charts (Fig. 10). These charts effectively present time-series data, facilitate cloud storage, and aid air quality analysis through visualization of parameter fluctuations, particularly relevant for capturing rapid changes in air conditions.

3.7 Virtuino app GUI and notification



(a) **(b)** **(c)**

Fig. 11 *(a) First picture; (b) Second picture; (c) Second picture*

Upon Virtuino app development completion, users will access the system's interface directly from their smartphones. The Virtuino GUI mirrors air quality parameters displayed on ThingSpeak, enabling data visualization across the TTN website, ThingSpeak platform, and the Virtuino app. The Virtuino display prioritizes clarity, featuring well-defined scales and parameter ranges corresponding to AQI levels for easy user comprehension. Additionally, an alarm system with configurable thresholds has been implemented. Alerts, as shown in Fig. 11(c), are delivered via SMS to user mobile phones.

4. Conclusion

This project presents an IoT-based Air Quality Monitoring System utilizing LoRaWAN for outdoor environments. The system features a portable wireless monitoring device equipped with MQ9, MQ135, and Dust sensors to detect gas and particulate matter concentrations, respectively. Additionally, a DHT11 sensor measures ambient temperature and humidity. Real-time data on these parameters is transmitted to the cloud server via LoRaWAN, enabling smartphone access through a custom Virtuino mobile app. The app displays real-time data and triggers alarms when pollutant levels breach pre-defined thresholds. While currently a prototype, this system holds promise as a valuable tool for public air quality awareness.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm their contribution to the paper as follows: study conception and design: Mohd Amin Sulimat, Norshidah Katiran; data collection: Mohd Ammiin Bin Sulimat; analysis and interpretation of results: Mohd

Ammiin Sulimat; draft manuscript preparation: Mohd Ammiin Sulimat. All authors reviewed the results and approved the final version of the manuscript.

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