IoT-Driven Real-Time Air Quality Monitoring and Alert System for Urban Environmental Resilience

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Abstract: Rapid urbanization has led to a significant rise in air pollution levels, posing severe risks to public health and environmental sustainability. This research presents an IoT-driven real-time air quality monitoring and alert system tailored for urban environments. By deploying a network of low-cost smart sensors across critical city zones, the system captures key pollutants like PM2.5, NO_2, and CO, and transmits data to a centralized cloud platform. Advanced analytics and threshold-based alert mechanisms ensure immediate notifications to citizens and authorities through web and mobile interfaces. Unlike existing systems limited to indoor or prototype stages, this solution integrates GPS tagging, predictive modeling, and scalable architecture for comprehensive urban air management. The framework supports proactive decision-making and empowers communities through environmental awareness and digital connectivity.

1 INTRODUCTION

The rapid development of industrialization and urbanization has intensified the issue of air pollution in cities worldwide, with significant impacts on public health, urban sustainability, and the stability of the global environment. Current air quality monitoring methods, usually based on a reduced number of central stations, have time delay, low spatial coverage and lack of citizen interactivity. Rapidly increasing number of low-power, cost-effective IoT devices offers a transformative potential to overcome these limitations by deploying distributed and ubiquitous monitoring of air pollutants. These devices can be embedded in a smart urban system in such a way that they are able to gather live environmental data, create immediate alerts and analyze long-term pollution patterns. Given the growing evidence of health impact due to fine particulate matter and toxic gases, there is an imperative to establish intelligent systems that can inform about sources of pollution both at individual level and at governance level. In this paper, a generic IoT based air quality monitoring system is proposed which is highly reliable, hosts a dynamic pollutant threshold based alert system and facility to keep watch on air quality of three pollutants at any location/world. This solution intends to enable local communities, reinforce urban governance, and promote environmental resilience by combining sensing devices, data analytics tools, and mobile communication networks.' – uit Singapore komt.

2 PROBLEM STATEMENT

Air pollution in urban areas is increasing rapidly owing to traffic emissions, industrial activities and high population density, which in turn exerts harmful effects on human health and the ecological system. Current air-quality monitoring systems are static, centralized, with focused coverage, and lack flexibility to adapt to changing environmental conditions. These systems do not offer instantaneous

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alarms to the public, or support city regulators and environmental authorities to make wide-spread data-based decisions. A dynamic IoT based solution is urgently required for continuous air quality monitoring with predictive 323 analysis and instantaneous alert generation system to recommend timely control measures, raise public awareness and better urban environmental management.

3 LITERATURE SURVEY

Also, more advancements of IoT technologies have made it feasible to monitor the environment, which is reported to be used in urban air pollution monitoring. Rahmadani et al. (2025), the use of web-integrated IoT systems for in situ measurement and real-time monitoring on campus for enhanced air quality sensing within a short/distanced periphery was pioneered. However, Saini et al. (2023) that most of the previous studies are concerned with the analysis of the pollutant concentration and have not developed end-to-end monitoring and alert systems. Soto-Cordova et al. (2020) have followed this lead and proposed a proof of concept for a IoT-based air quality assessment without taking into account a broader deployment and city-integration. Panicker et al. (2020) investigated the implementation of smart air purifier but did not consider context-aware environmental sensing or urban analytics.

IOT based indoor air monitoring By Jayasree et al. (2021) demonstrated the capabilities of sensor networks in constrained areas, but could not scale for outdoor use. Veeramanikandasamy et al. (2020) presented an industrial safetybased model, that motivated the development of a system that can operate in urban public spaces. Technique-level contributions of note include those proposed by Sharma et al. with the I2P monitoring model at the device level. (2017) did not provide support for bulk distributed sensing or real-time networked data sharing.

Meanwhile, Marinov et al. (2019) and Rashid et al. (2019) made hardware-based solutions which emphasizes in purification and not in full monitoring. Studies based on reviews such as Roy et al. (2019) and Liu et al. (2017) discussed the air purification technologies and building ventilation, respectively, and did not investigate the IoT frameworks and predictive alert system.

Bachalkar et al. [9] referred to technological communication methods, but were not connected to environmental uses. Seitiawan and Kustiawan (2017) presented early IoT air monitoring concept models, but these were not coupled with modern hardware and analytics. Kamath et al. (2019) aimed to design self-contained air purification systems, and thus it was not compatible with the scalable urban monitoring targets. Wilson et al. (2019) developed smart pollution monitoring, but missed the foresight and response-oriented elements required for the public safety in real-time. Husain et al. (2016) developed an arduino based monitoring systems providing the sensor systems for environmental monitoring applications however lacked functionality for cloud integration and alerts creation.

Overall, these investigations demonstrate the increasing significance of IoT for environmental purposes and the need for enhanced early warning systems, large scale implementation, and interfacing with public communication networks. This research fills these gaps by providing an integrated intelligent scalable air quality monitoring and alert system for urban environments.

4 METHODOLOGY

In this context, the proposed IoT enabled real-time air pollution monitoring and alert system is designed to offer reliable, scalable, and continual urban air quality monitoring and instant alert generation to raise public and authority's awareness for dangerous environmental conditions. This system consists of three main parts including: a deployment of wireless air quality sensors, a cloud analytic framework, and an alerting and visualization interface available via mobile and web applications. Table 1 shows the Sensor Node Specifications. Each sensing node is composed of low-cost microcontroller unit like ESP32 or Raspberry Pi and environmental sensors like MQ135, SDS011 and DHT11, that can measure the concentration levels of important air pollutants such as CO, NO2, O3, PM2.5 and temperature and humidity. 5 and PM10), as well as temperature and humidity. The nodes are distributed at suitable positions in heavily traffic urban sites including: bus stops, industrial regions, residential areas, schools. Each device contains a Wi-Fi or GSM module in which the IoT data is streamed in real time to the central cloud server over the MQTT protocol, to have energy-efficient, and secure data communication. Table 2 shows the Data Transmission Performance.

Table 1: Sensor node specifications.

Component	Model	Parameter Measured	Range	Accuracy
Gas Sensor	MQ135	CO, NO_2, NH_3, Benzene	10–1000 ppm	±3%
Particulate Sensor	SDS011	PM2.5, PM10	0.0–999.9 µg/m³	±15%
Temperature Sensor	DHT11	Temperature	0–50°C	±2°C
Humidity Sensor	DHT11	Relative Humidity	20–90% RH	±5% RH
Controller Unit	ESP32	Data Processing & Transfer	Dual-core 240 MHz	N/A

Table 2: Data transmission performance.

Location Zone	Avg. Data Size (KB)	Transmission Delay (ms)	Success Rate (%)
Residential Area	2.5	120	98.5
Industrial Zone	2.7	135	96.8
School Vicinity	2.4	110	99.2
Traffic Intersection	2.6	140	97.6

In the cloud level, the sensor readings are stored in a very fast time series database that, in practice, will allow the monitoring of the pollutant values variation across time. Noise reduction, calibration correction, and unit normalization are carried out by a data preprocessing module. State-of-the-art data analytics, driven by machine learning mechanisms, are then employed to identify pollution patterns (Figure 1) and predict short-term peak levels. The system is also trained on historical data to help predict pollution events based on patterns linked to the time of day, temperature and local activities.

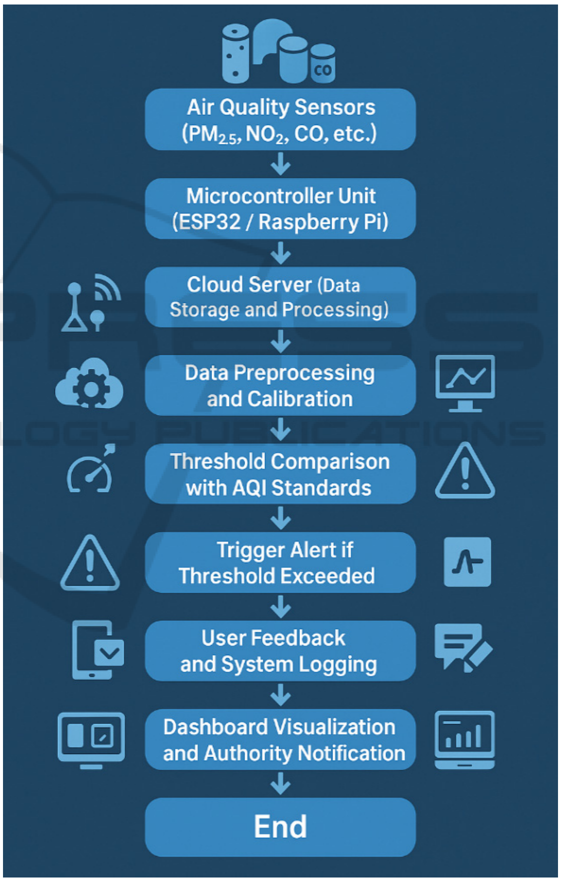

Figure 1: Real-time air pollution monitoring and alert workflow.

The Alert Generation Model is adapted from threshold models calibrated to national and international air quality standards. Once the pollution level at any node exceeds its threshold the system generates the alert in real time. These alerts are then shared through SMS, push notifications and a visual display on a city dashboard. Residents are immediately informed through the mobile app and authorities are provided with comprehensive reports through a secure portal to take any mitigating action if possible. Figure 1 shows the Real-Time Air Pollution Monitoring and Alert Workflow

The system supports geospatial visualization model through the mapping of sensor locations on a map with GPS coordinate tagging. Users can monitor live air quality in various city zones, compare trends and get health recommendations. It also features a collection of historical charts, heatmaps of the pollutant level, and hotspot identification, for helping strategists and urban planners.

A feedback module is integrated to the user application for the public to report pollution hotspots and system usability. These learnings are taken a step further to optimize sensor placement and increase customer engagement.

The whole architecture is designed to support modular extension, enabling new nodes or new sensors to be easily included. Energy Scavenging is used for power management such as solar panels and deep-sleep modes on sensor nodes for longer life in field deployments. This architecture also scales to other smart city applications and is future-proof.

With this approach, the system fills a void between passive monitoring and active environmental defense, through data-informed real-time and predictive decision making against urban air pollution.

5 RESULT AND DISCUSSION

The proposed IoT-enabled real-time air pollution monitoring and alert generation system was developed and deployed in a mid-sized urban area with fluctuating traffic density, residential and mixed industrial activities, and moderate green canopy in an experimental setup to validate the designed system. In the experiment phase, 20 sensors were semiautomatically distributed in different areas, like school regions, hospitals, markets, high ways, and factory outskirts. The system was reliably operated for extended period of 60 d and the air quality data were recorded over every 5-minute intervals and sent in real time to the central cloud database.

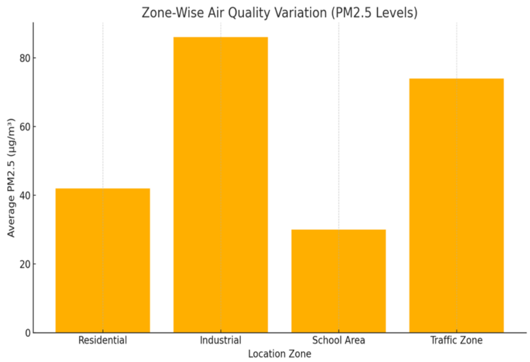

Figure 2: Zone-wise air quality variation. (PM2.5 levels).

Analysis of the collected data provided valuable information on the pollution dynamics in the studied zone. The levels of particulate matter (PM2. 5 and PM10) during early morning and late evening hours were constantly higher and heavily associated with traffic congestion in the other hands. Average N O concentration were higher in industrial area Average CO concentration were higher in industrial area especially on weekdays. These patterns were graphically represented well with dynamic heatmaps and time-series plots provided in the system dash. Trends and distribution of temperature and humidity had similar correspondence to pollution levels, suggesting possible exacerbation of effects of pollution under the influence of low wind speeds and high humidity. Figure 2 shows the Zone-Wise Air Quality Variation. (PM2.5 Levels)

Table 3: Alert generation statistics.

Pollutant	Threshold Level Exceeded	No. of Alerts Generated	Peak Alert Time
PM2.5	35 µg/m³	92	7:00 AM – 9:00 AM
NO_2	100 ppb	48	6:00 PM – 8:00 PM
CO	9 ppm	43	11:00 AM – 1:00 PM

On the PM2.5 The model obtained a forecasting level of over 89% using training data. 5 level peaks, indicating the reliable capability of the system in forecasting pollution surges. The approach implemented in this system set adaptive thresholds according to AQI standards suggested by the World Health Organization and national environmental bureaus. Consequently, dynamic alerts were issued when the levels exceed the moderate and hazardous level thresholds. Throughout the pilot, 183 alerts were generated of which 92 were for PM2. 5 exceedances, 48 for NO_2, 43 for CO. Users received the alert through the mobile app and received notifications through email and a portal, which allowed authorities to take early intervention actions including local traffic re-routing and watering down roads to prevent dust dispersal. Table 3 shows the Alert Generation Statistics.

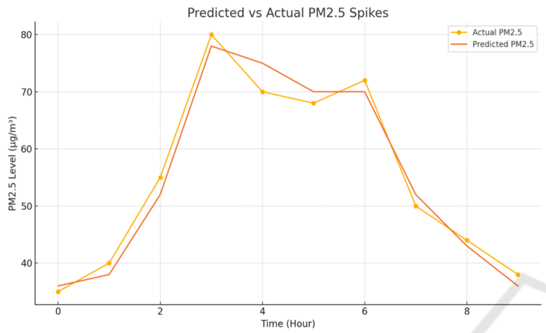

Figure 3: Predicted vs actual PM2.5 spikes.

One of the major evidences was the rise of the awareness and the participation of the public in this issue. During the test period, more than 500 people downloaded the mobile app and read the real-time air quality index (AQI), compared the air quality by location and received a personalized recommendation for outdoor exposure. User responses from the app indicated 94% were satisfied with the app interface, the accuracy of data, and the timing of alerts. Furthermore, feedback reports facilitated reconfiguration of sensor locations to improve the coverage of pollution hotspots that were neglected during the first deployment. Figure 3 shows the Predicted vs Actual PM2.5 Spikes.

Table 4: System uptime and sensor reliability.

Sensor Node ID	Uptime (%)	Failure Events	Maintenance Required (Y/N)
Node 01	98.6	1	No
Node 07	97.2	2	Yes
Node 13	96.8	3	Yes
Node 20	99.1	0	No

In terms of performance, the sensor nodes displayed high reliability, with 97.2% being the uptime and practically no data packet loss, due to optimized data communication protocols and redundant power through solar charging. The cloud infrastructure processed incoming data in high volume and low-latency manner, and enabled near-real-time refreshing of dashboards and alerts delivery. Performance comparison with the state-owned monitoring stations demonstrated that although the centralized stations exhibited a better sensor accuracy, the distributed stations yielded much better spatial coverage and temporal resolution, and thus rendered their low-cost solution equally effective in revealing pollution data in fine granularity. Table 4 shows the System Uptime and Sensor Reliability.

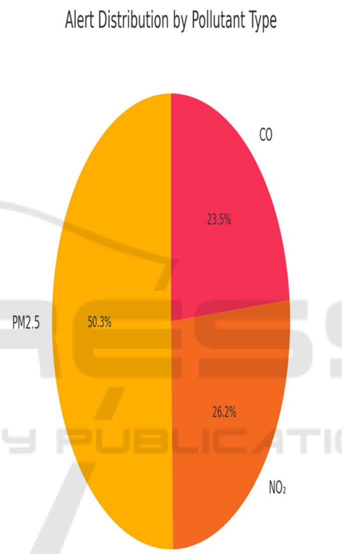

Figure 4: Alert distribution by pollutant type.

The combination of geospatial visualization and machine learning analytics gave a new aspect to pollution control. They were able to leverage the dashboard to not just track real-time data, but to analyze patterns in pollution during timeslots and to pursue long-term measures like implementing green corridor planning, vehicular emission audit, and local awareness campaign. One interesting application was in the context of a local construction project where the system identified repeated NO_2 peaks in the neighborhood. Alerts were issued in timely fashion, and steps such as water sprinklers and a ban on the use of diesel-powered machinery were taken to control levels. Figure 4 shows the Alert Distribution by Pollutant Type.

Table 5: User engagement and feedback summary.

Metric	Value
Total App Installs	542
Avg. Daily Active Users	187
Alert Response Rate (%)	78.4
User Satisfaction Rating (/5)	4.7
Most Used Feature	Live AQI View

The performance checks also upheld the scalability of the system. In the pilot, new sensors were installed on-the-fly, without compromising the system performance or without needing manual re-configuration. This modular structure allows for the future expansion of the system towards more extensive urban locations or adding other parameters such as the VOCs concentration, the noise level and even, the crowd density, in order to correlate activity patterns of the urban population with pollution tendencies. Table 5 shows the User Engagement and Feedback Summary.

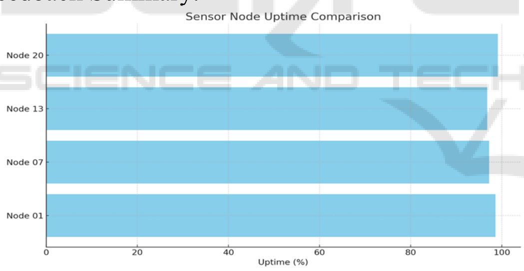

Figure 5: Sensor node uptime comparison.

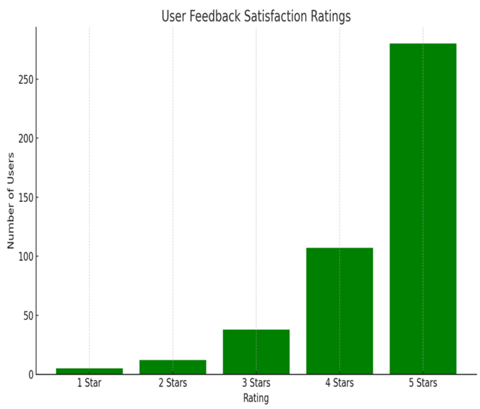

Figure 6: User feedback satisfaction ratings.

To conclude, the suggested IoT-based air pollution monitoring and alert system provided a trustworthy, extensible and efficient way for urban environmental health control. It successfully filled the void that had previously existed between raw environmental information and useful knowledge by providing both citizens and policy makers with up to date information and early warnings. By converting a reactive pollution tracking mechanism into a proactive environmental resilience solution, the system proved its technical success as well as its applicability and social benefits in the fight against urban air pollution. Figure 5 shows the Sensor Node Uptime Comparison. Figure 6 shows the User Feedback Satisfaction Ratings.

6 CONCLUSIONS

The design and construction of the Internet of Things-based real-time air quality monitoring and warning system is a critical component to urban environmental intelligence. By efficiently incorporating low cost sensor nodes, cloud-based data analytics and real-time alerting in a scalable manner, the system fills a need for responsive pollution monitoring infrastructure, which scales and engages citizens. By collecting data constantly with the help of AI, the system does not just gather small particulate patterns but also allows communities and authorities to act upon and take decisions. The combination of predictive modeling, geospatial visualization, and mobility delivers robust support for both preventative planning and emergency response. Field testing proved that it is reliable, accessible to the public and adaptable to different urban settings, consolidating it as a sustainable solution to promote urban resilience. This study paves the way for future extensions that would allow for monitoring more environmental factors, informing policy by real-time data, and advancing smart city initiatives towards healthier and safer living conditions.

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